High-energy Astrophysics Overview

Ke Fang
University of Wisconsin-Madison
P5 Town Hall at Argonne, Mar 23, 2023

The New Chapter of High-energy Astrophysics

- New since last P5: detection of **Gravitational Waves** and **High-energy neutrinos**!

Credit: AAS

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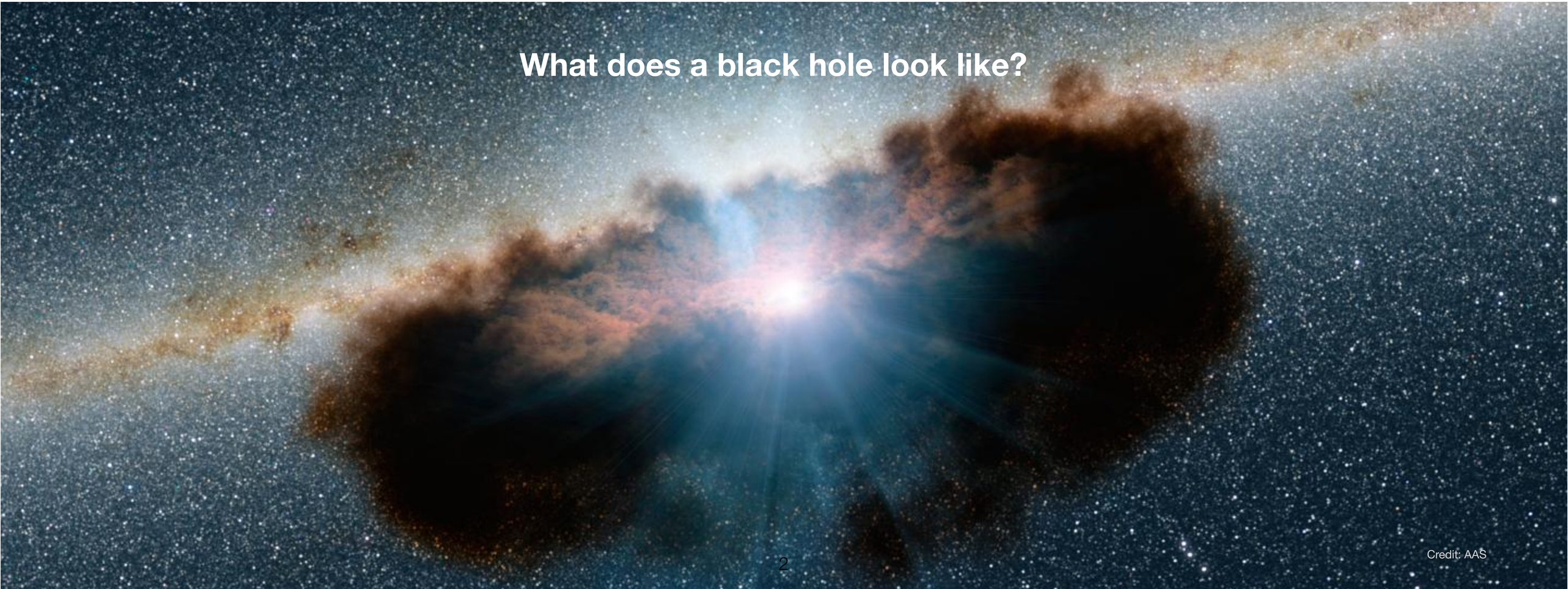

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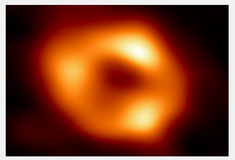

Sagittarius A*
Event Horizon Telescope
ApJL (2022)

What does a black hole look like?

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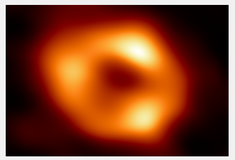

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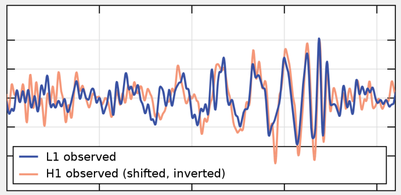

GW150914
LIGO Collaboration *PRL (2016)*

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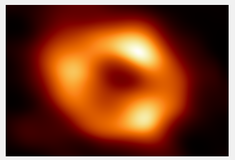

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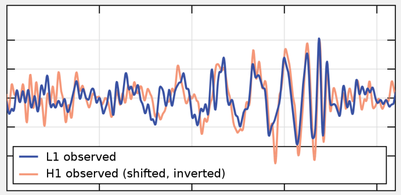

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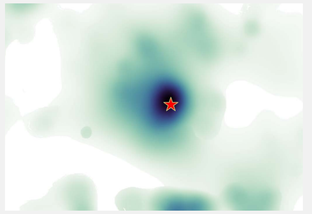

NGC 1068
IceCube Collaboration
Science (2022)

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The New Chapter of High-energy Astrophysics

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- This talk: **cosmic particles**, including high-energy **neutrinos, gamma-rays, and cosmic rays**

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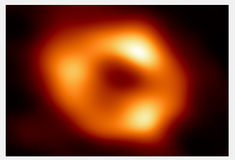

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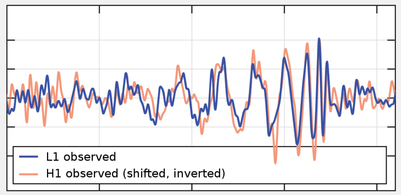

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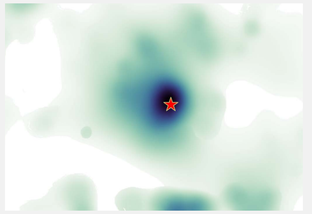

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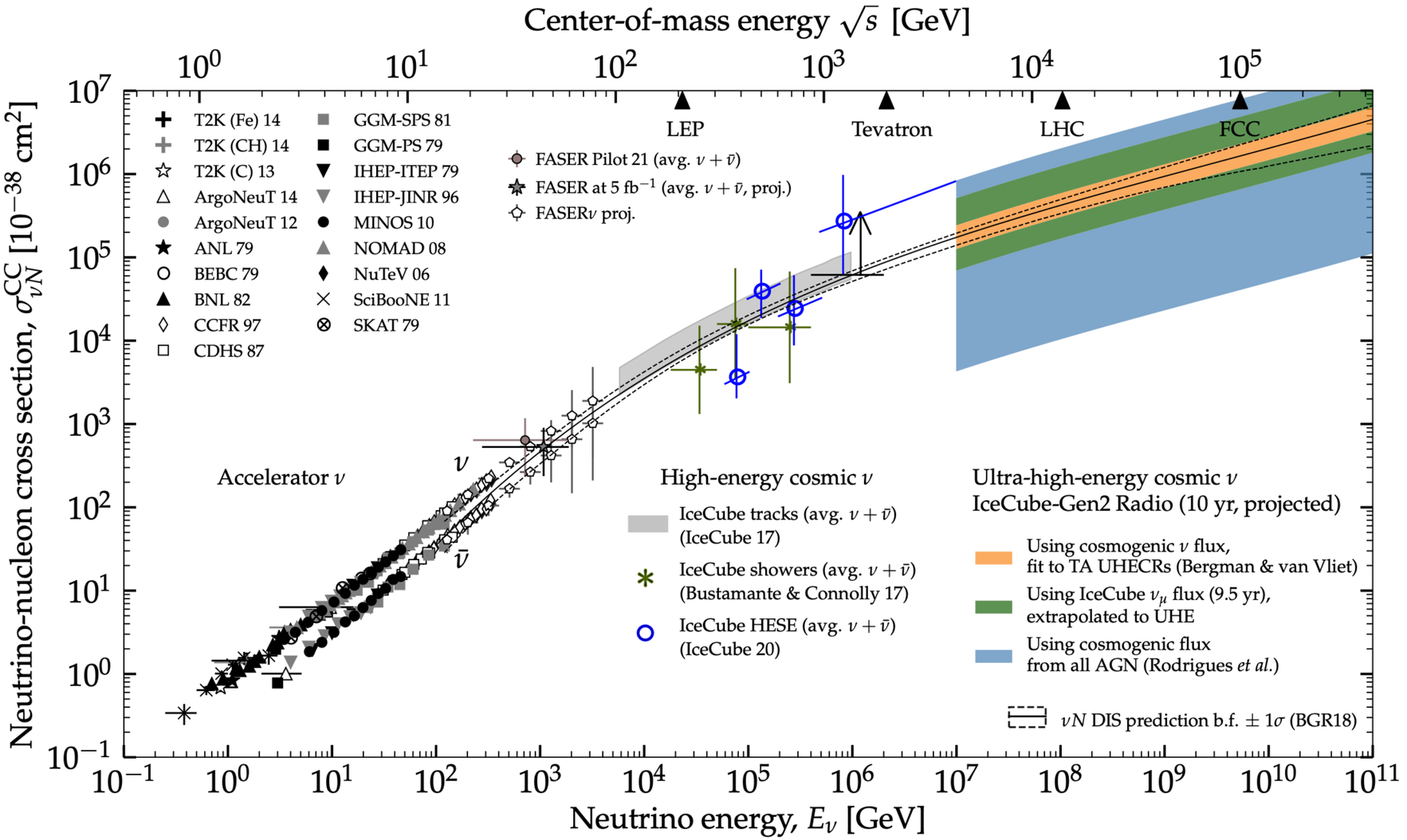
Particle Physics with Cosmic Particles

- Measure **properties of fundamental particles** at energies beyond the reach of man-made accelerators



Snowmass 21 CF7 report

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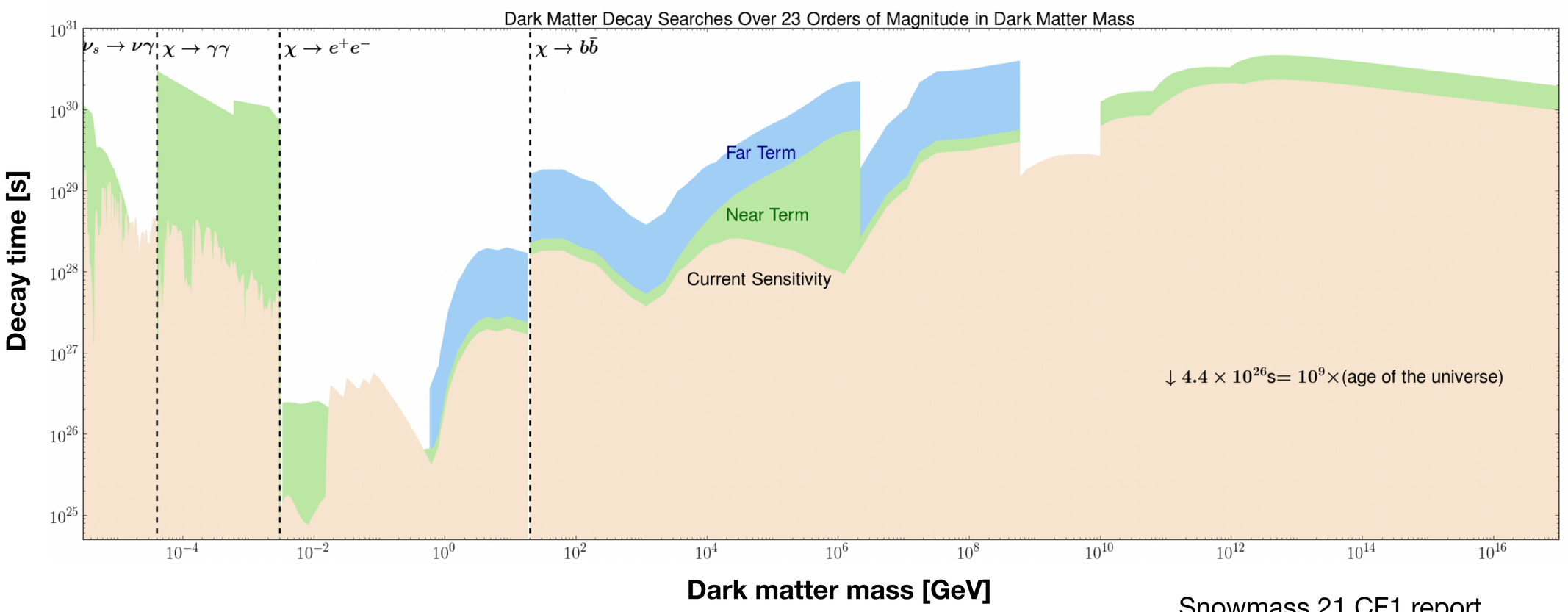

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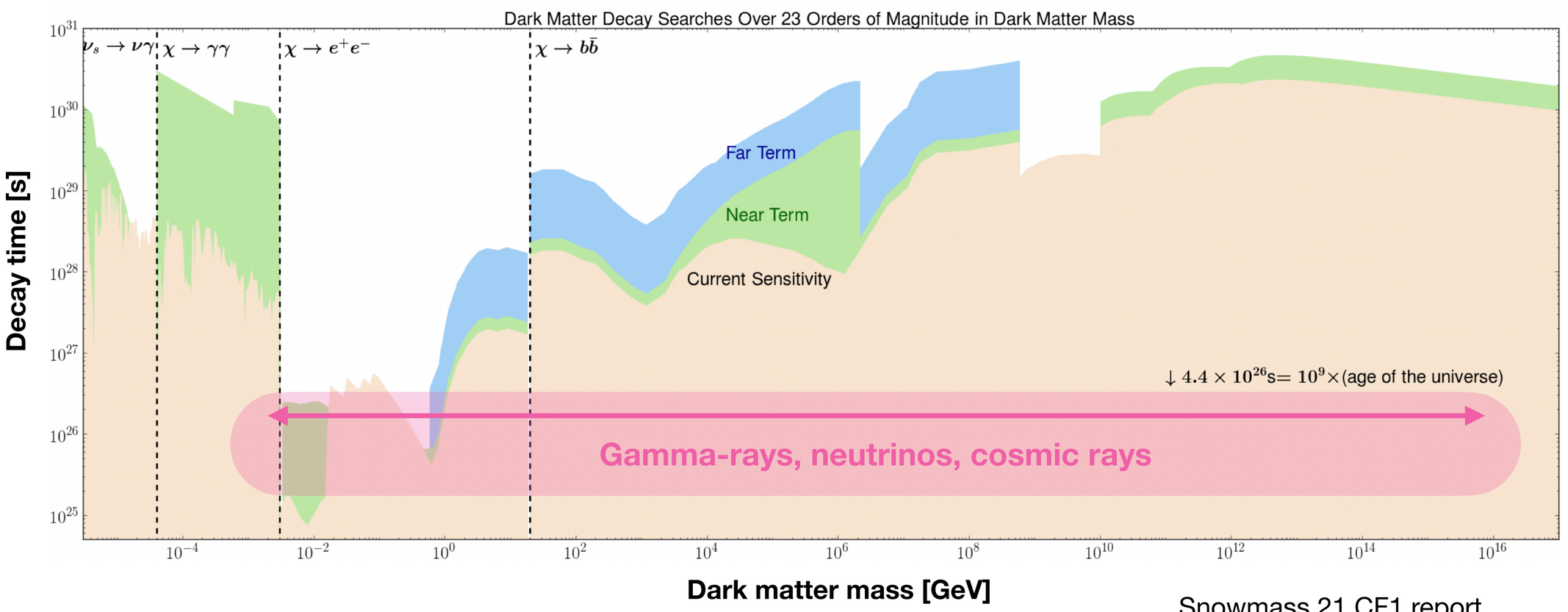

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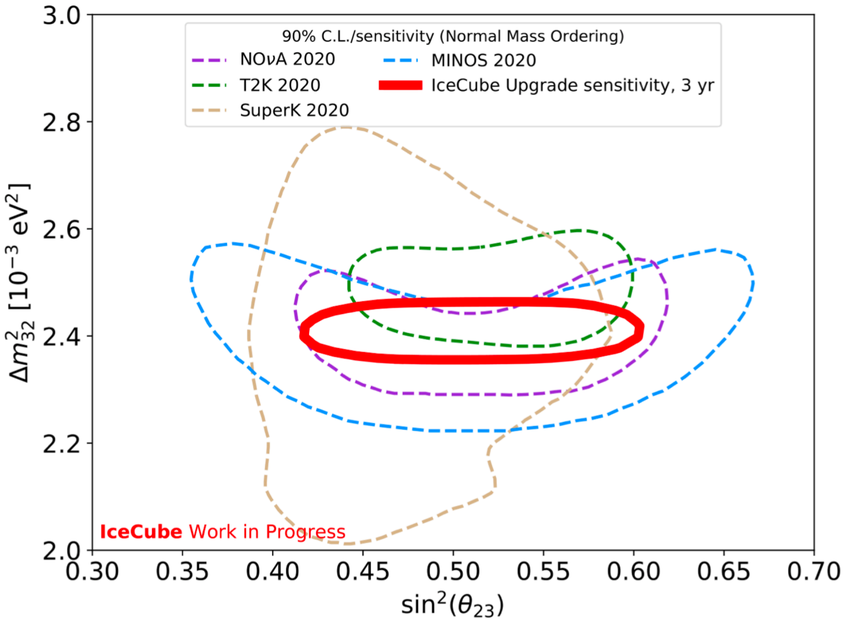

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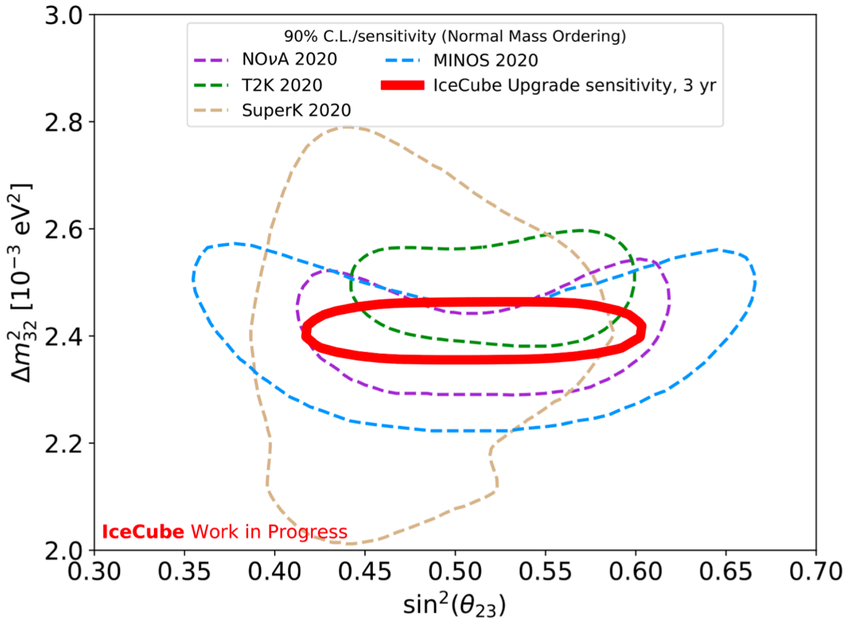
Complementary to particle physics facilities!



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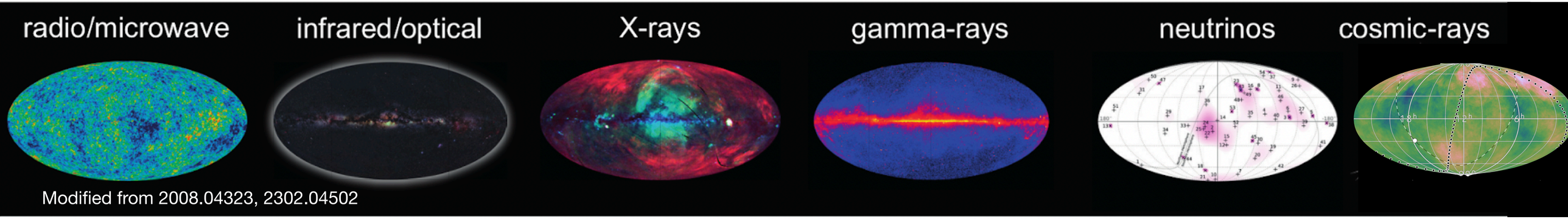
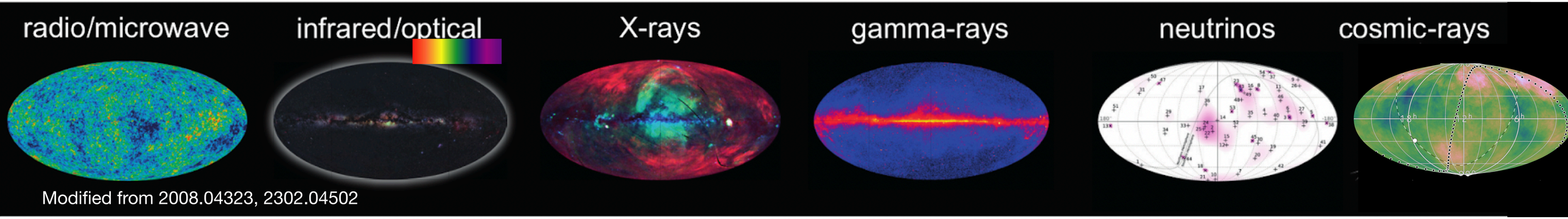


Modified from 2008.04323, 2302.04502

Astrophysics with Cosmic Particles

Visible light: 2-3 eV



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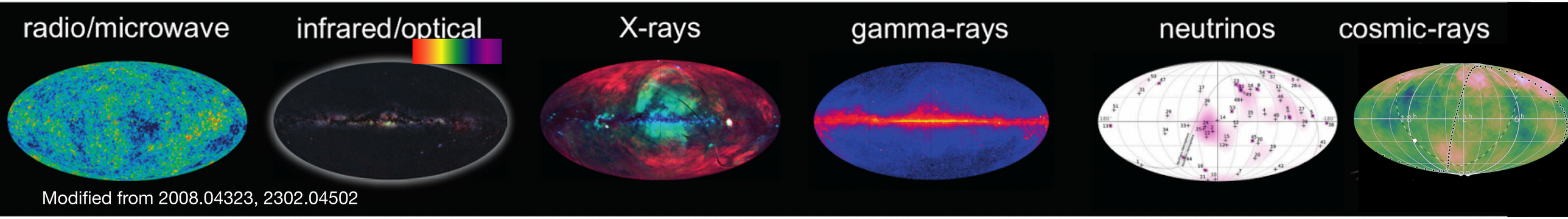

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Astrophysics with Cosmic Particles

Window of the soul

Visible light: 2-3 eV

Windows on the Universe

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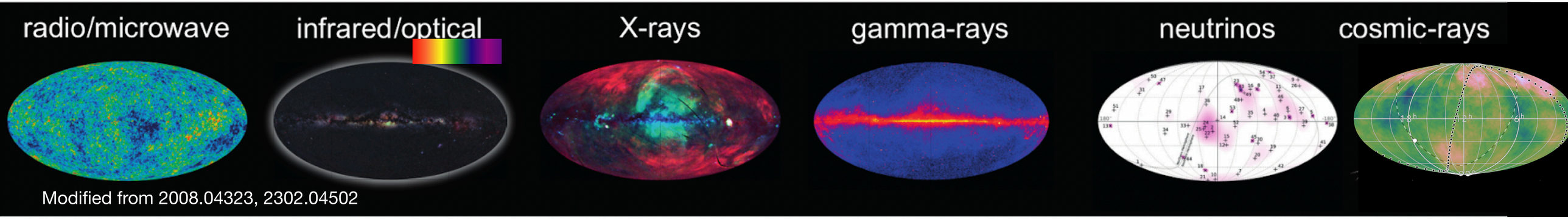

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A blooming field: what's learnt since last P5

- Existence
- Astrophysics
- Particle physics

A blooming field: what's learnt since last P5

- **Detection** of TeV-PeV astrophysical ν *[IceCube Science 2013, PRL 2014, 2015, 2020]* and 100 TeV - 1PeV γ *[HAWC PRL 2021, Tibet PRL 2021, LHAASO Nature 2021, Science 2021]*

- **Existence**
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- **Stellar-mass cosmos** probed by TeV γ : black holes *[HAWC Nature 2018, MAGIC Nature 2019, H.E.S.S Nature 2019, Science 2021]* and stellar wrecks *[HAWC Science 2017, PRL 2020, H.E.S.S Science 2022]*
- **Supermassive blackholes** probed by TeV ν and γ *[IceCube Science 2018ab, 2022, H.E.S.S. Nature 2020]*
- **Origin of cosmic rays**: dipole in the arrival direction of > 8 EeV cosmic rays *[Auger, Science 2017]*

- **Particle properties and interaction:** Measurement of multi-TeV ν–nucleon cross section and inelasticity *[IceCube Nature 2017]*, Glashow resonance *[IceCube, Nature 2021]*, fluctuations in muon number *[Auger PRL 2016, 2021]*, neutrino oscillations and flavor ratio *[IceCube PRL 2015, 2018]*
- **Constraints on dark matter** annihilation and decay signals *[H.E.S.S. PRL 2016, 2018, 2022, MAGIC PRL 2023, LHAASO PRL 2022, Auger PRL 2023]*
- **Constraints on BSM:** Lorentz invariance *[HAWC PRL 2020]*, sterile neutrinos *[IceCube PRL 2016, 2020, 2022]*, nonstandard interactions *[IceCube PRL 2022]*

What’s still unknown / need better answers

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- Where are the **PeV hadron colliders** (“PeVatrons”) in our Milky Way?
- How does nature **accelerate** particles to > 1 EeV?

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- **Particle properties and interaction**: mixing angles, cross sections at higher energies
- **Indirect searches**: what will be the fate of WIMPs and thermal dark matter?
- **BSM**: ν_τ appearance, sterile neutrinos, nonstandard interactions

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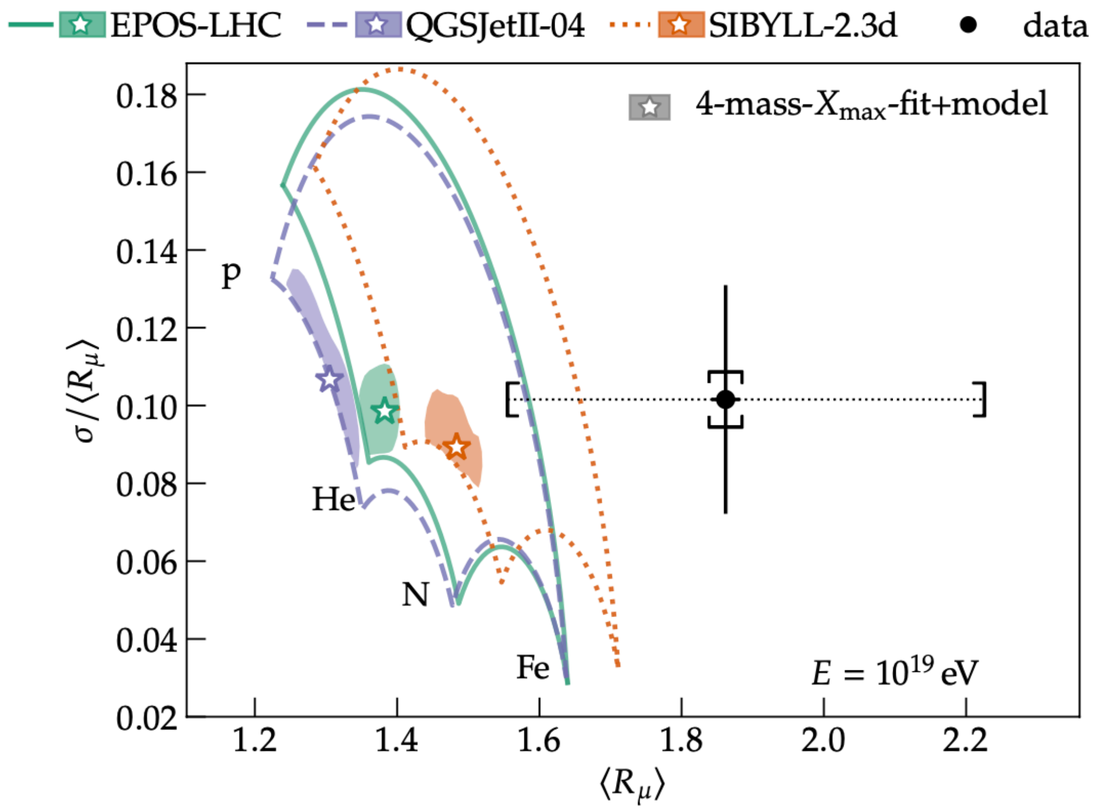

Auger Collaboration, PRL (2016, 2021)

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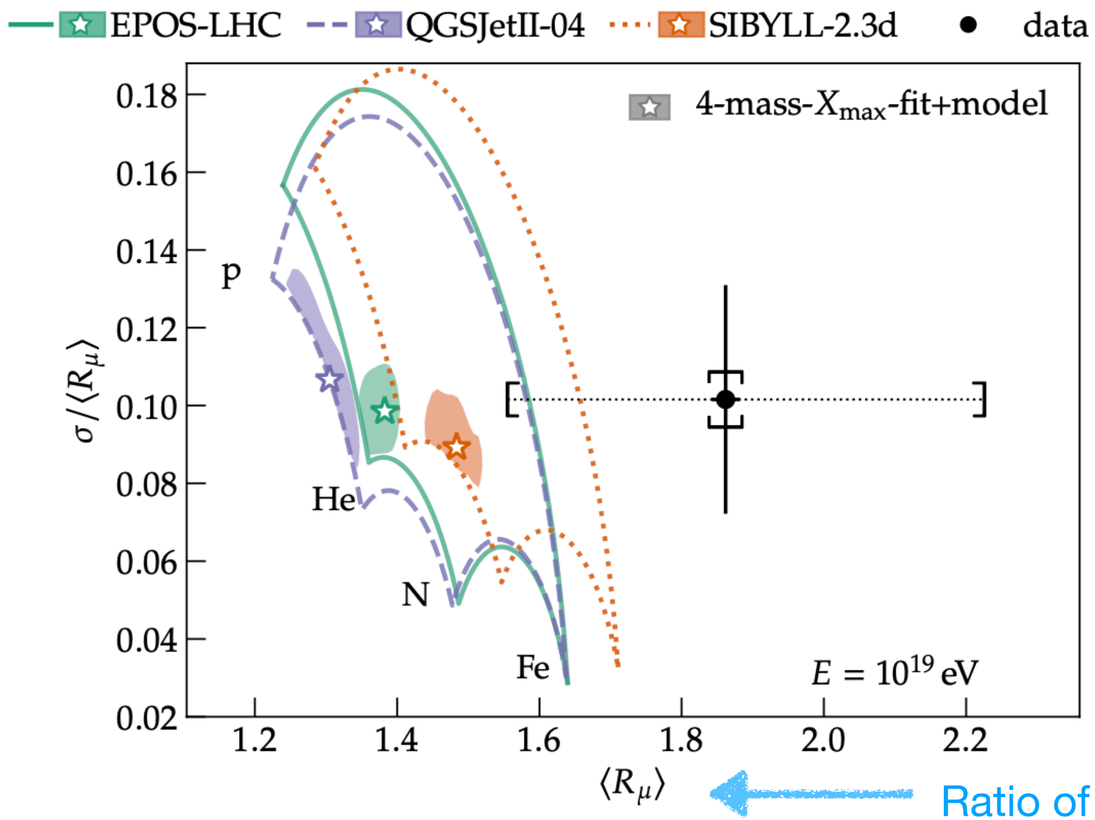

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Ratio of observed muon counts to model prediction assuming pure proton composition

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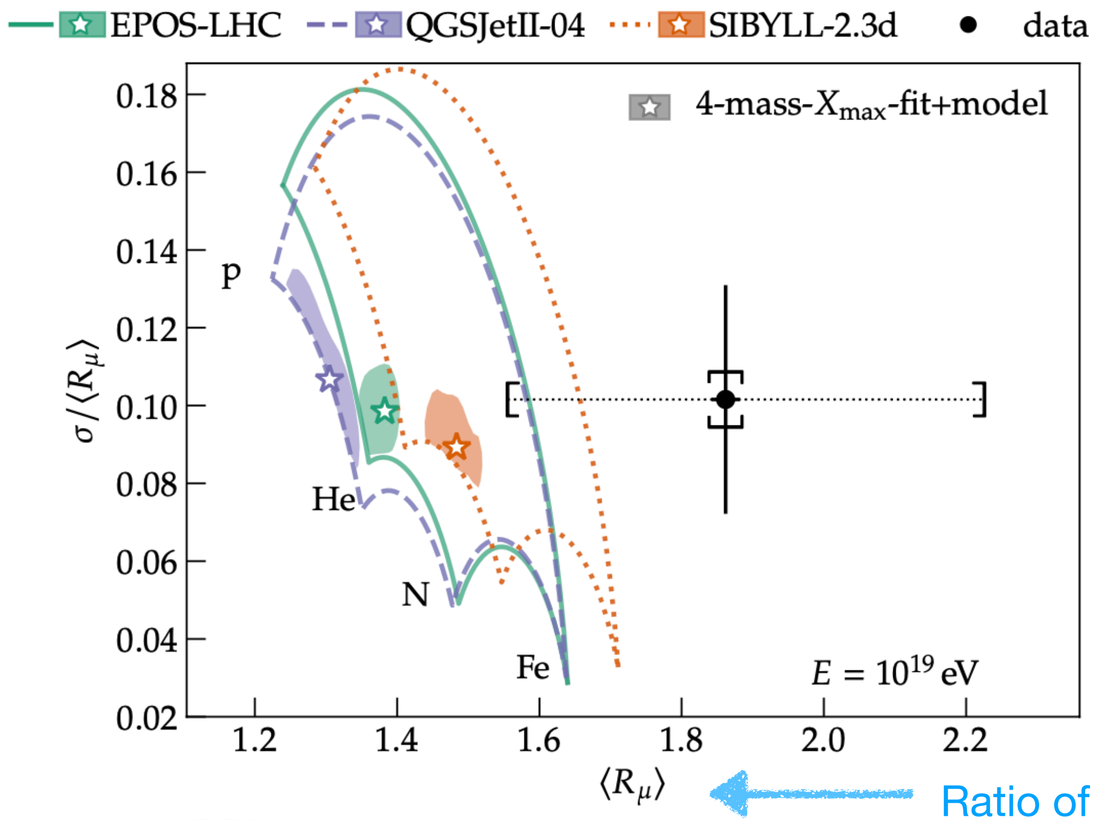
Deficit in model prediction of muons from hadron interactions.
Hint of BSM physics?



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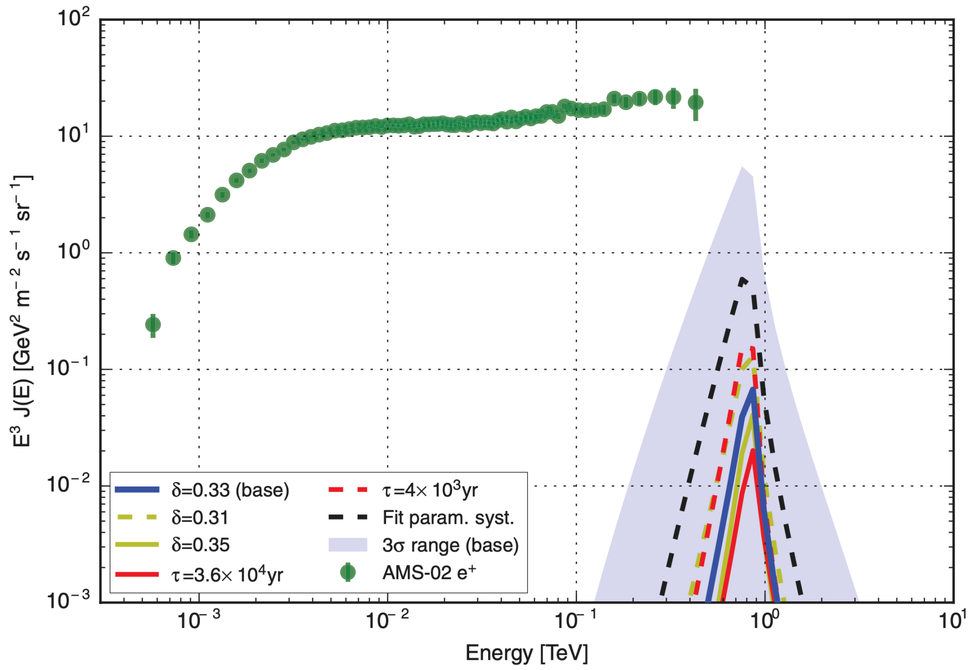

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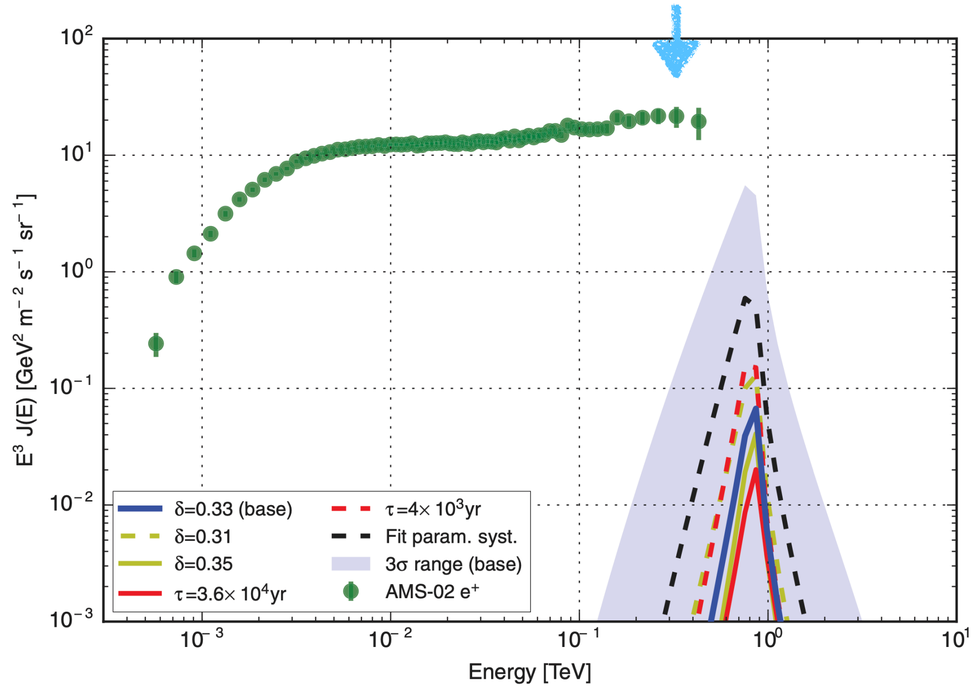

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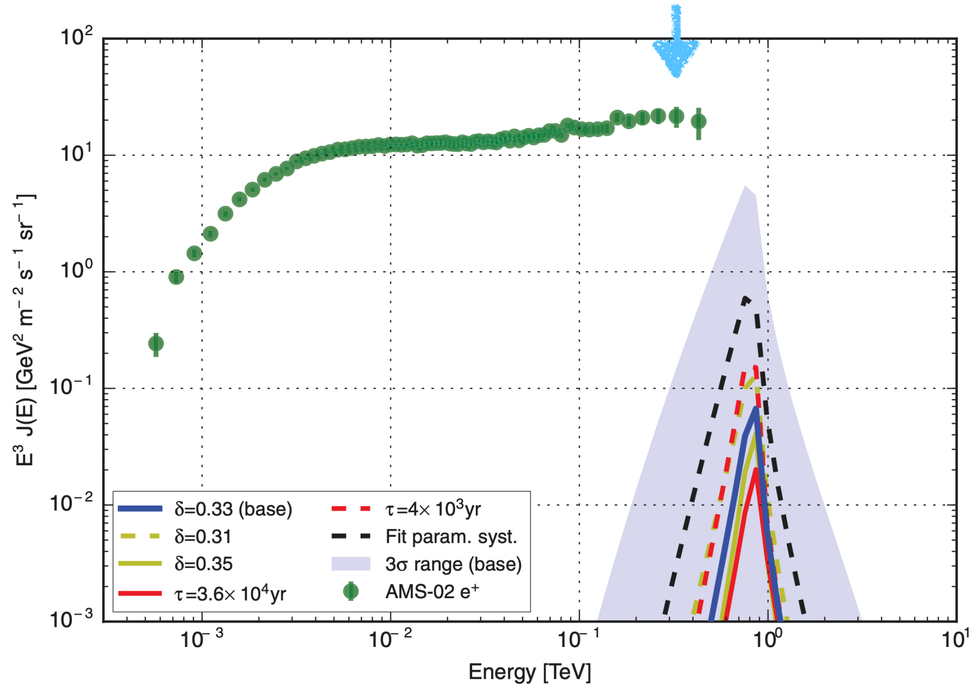

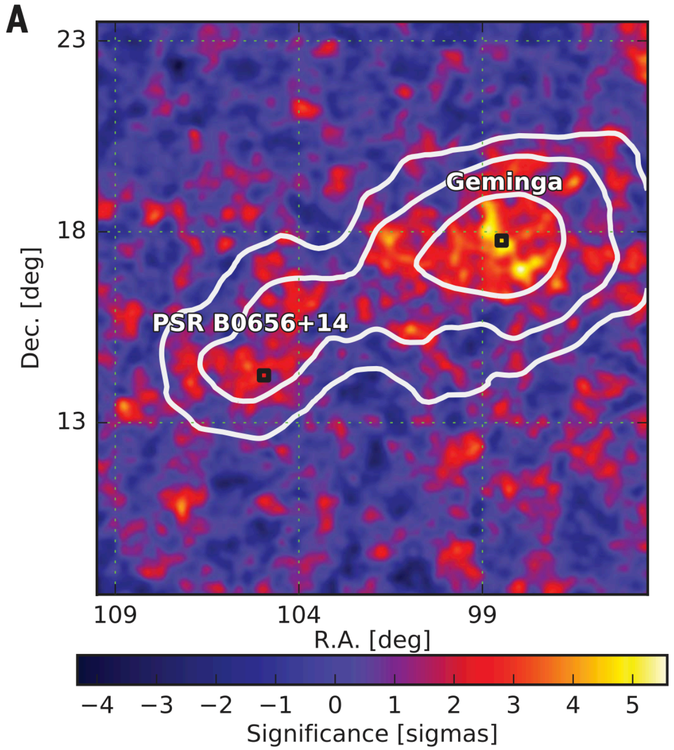

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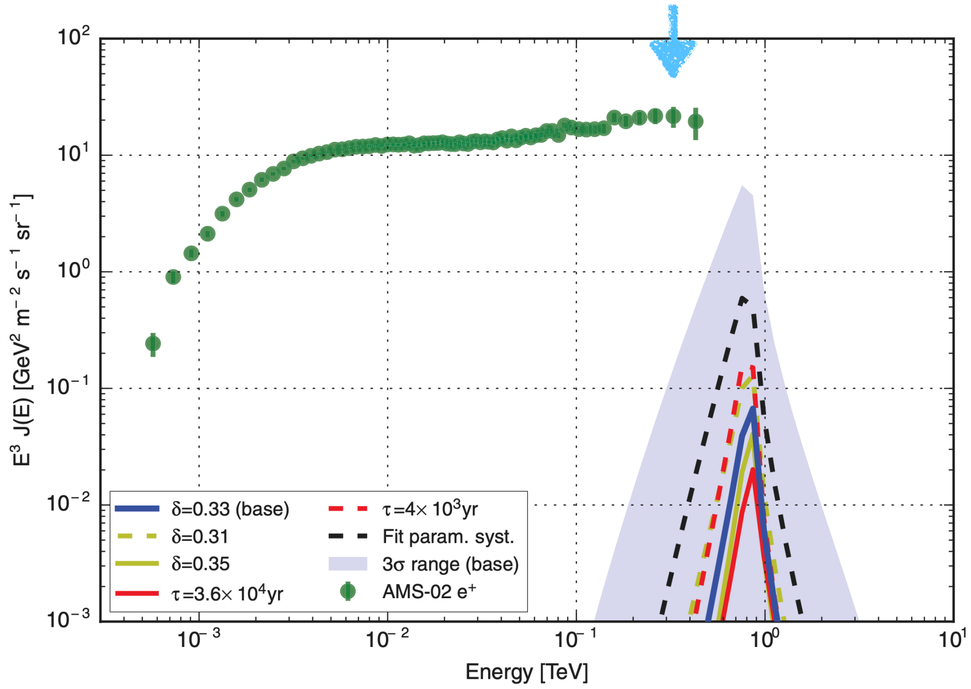

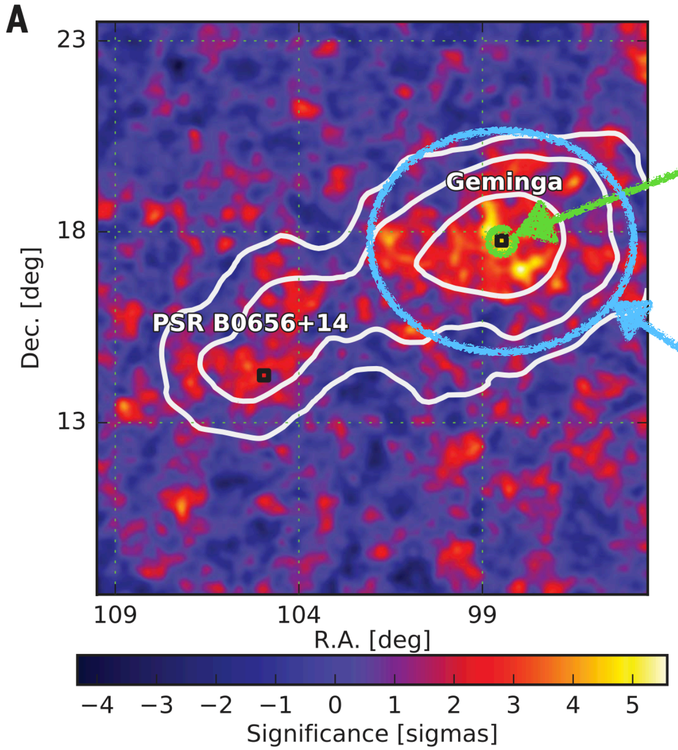

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Size of TeV halo

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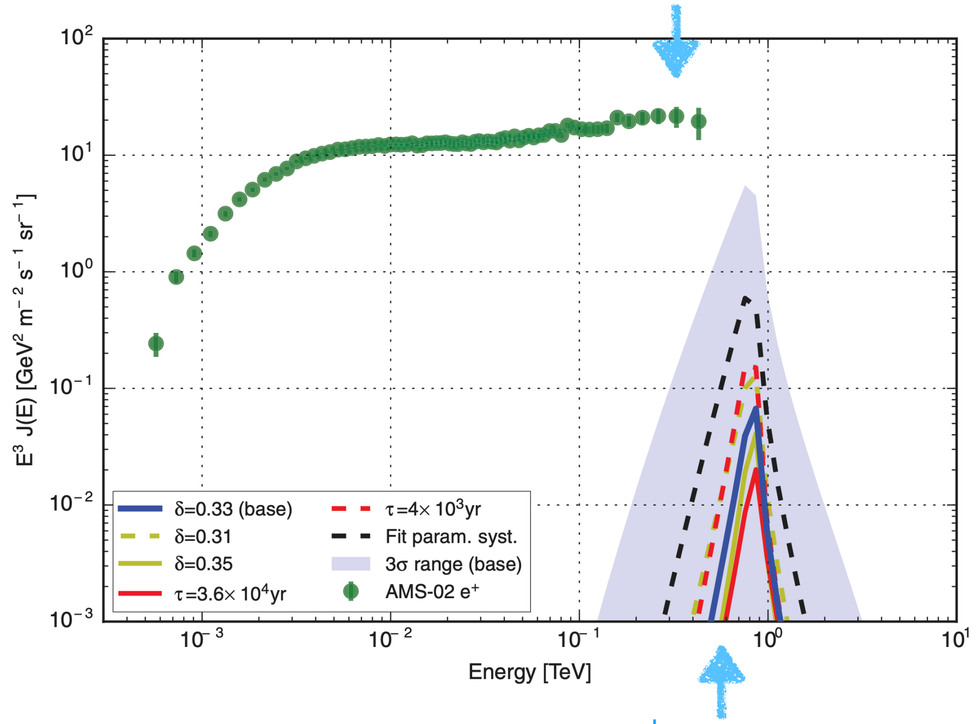
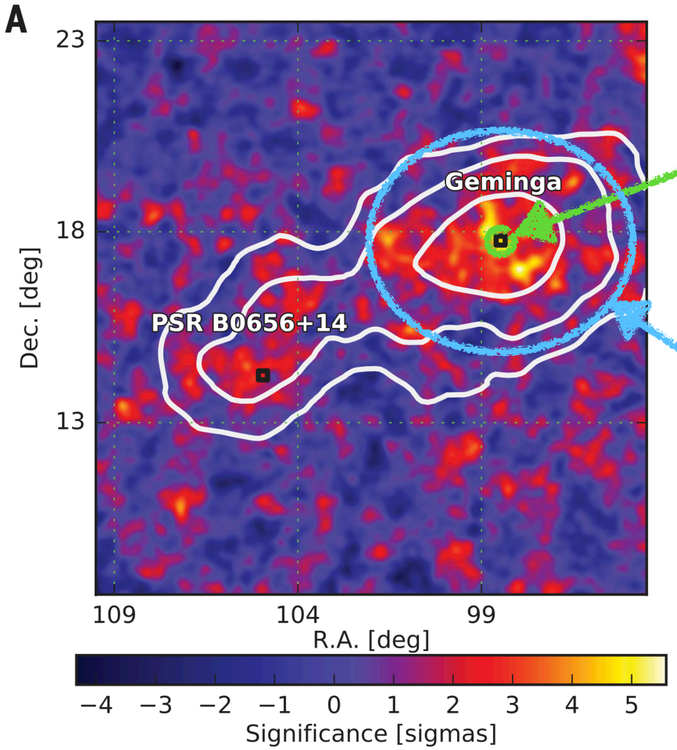


Lower e^+ expected at Earth due to confinement by TeV halo

Astrophysics "standard model" of middle-aged pulsars turned out wrong and impacted indirect searches



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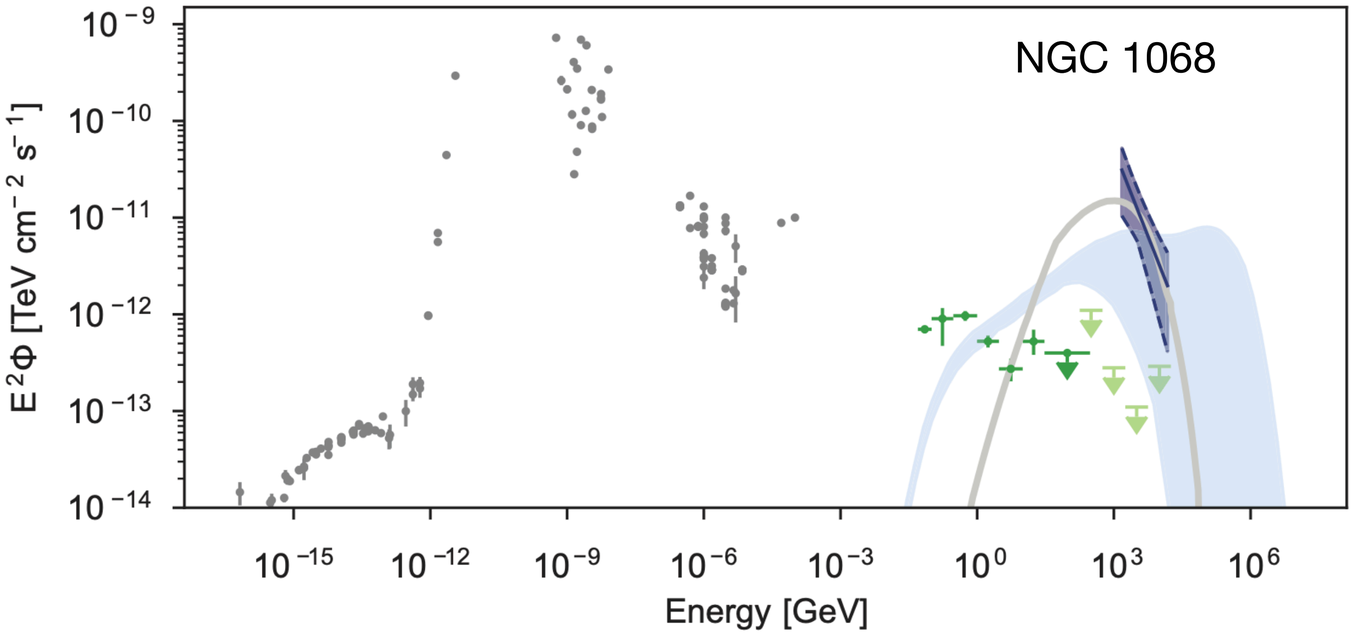

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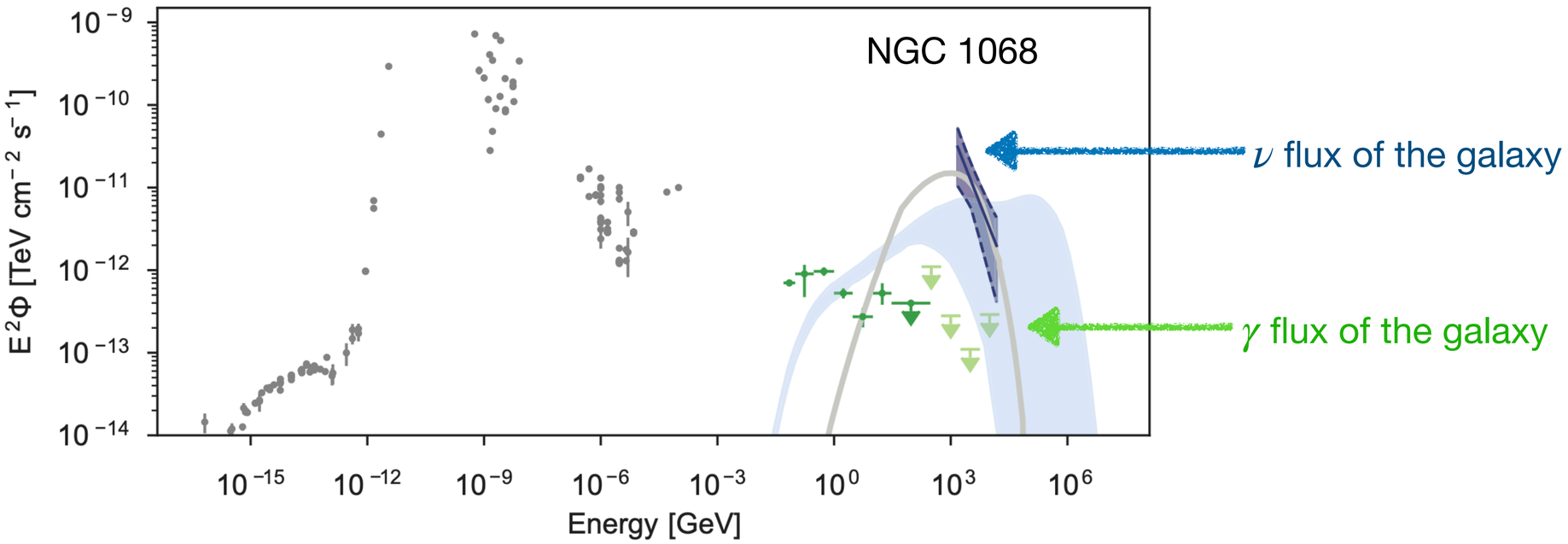

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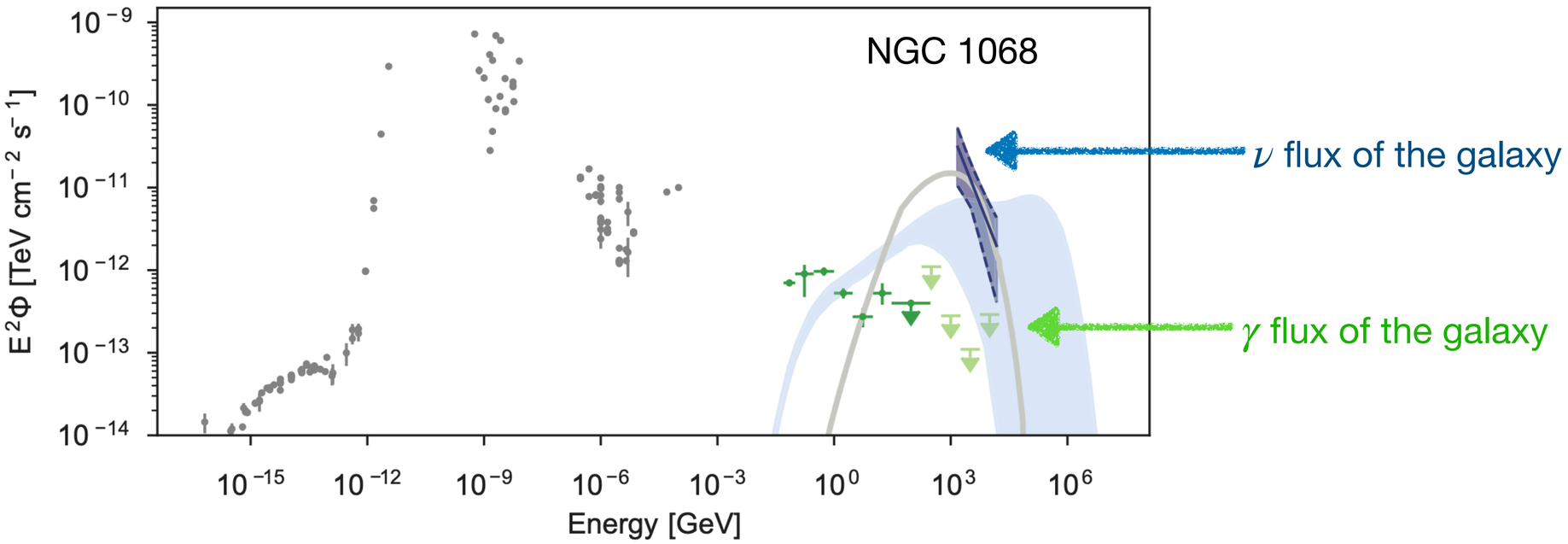
A new look of the high-energy Universe not seen through photons before!



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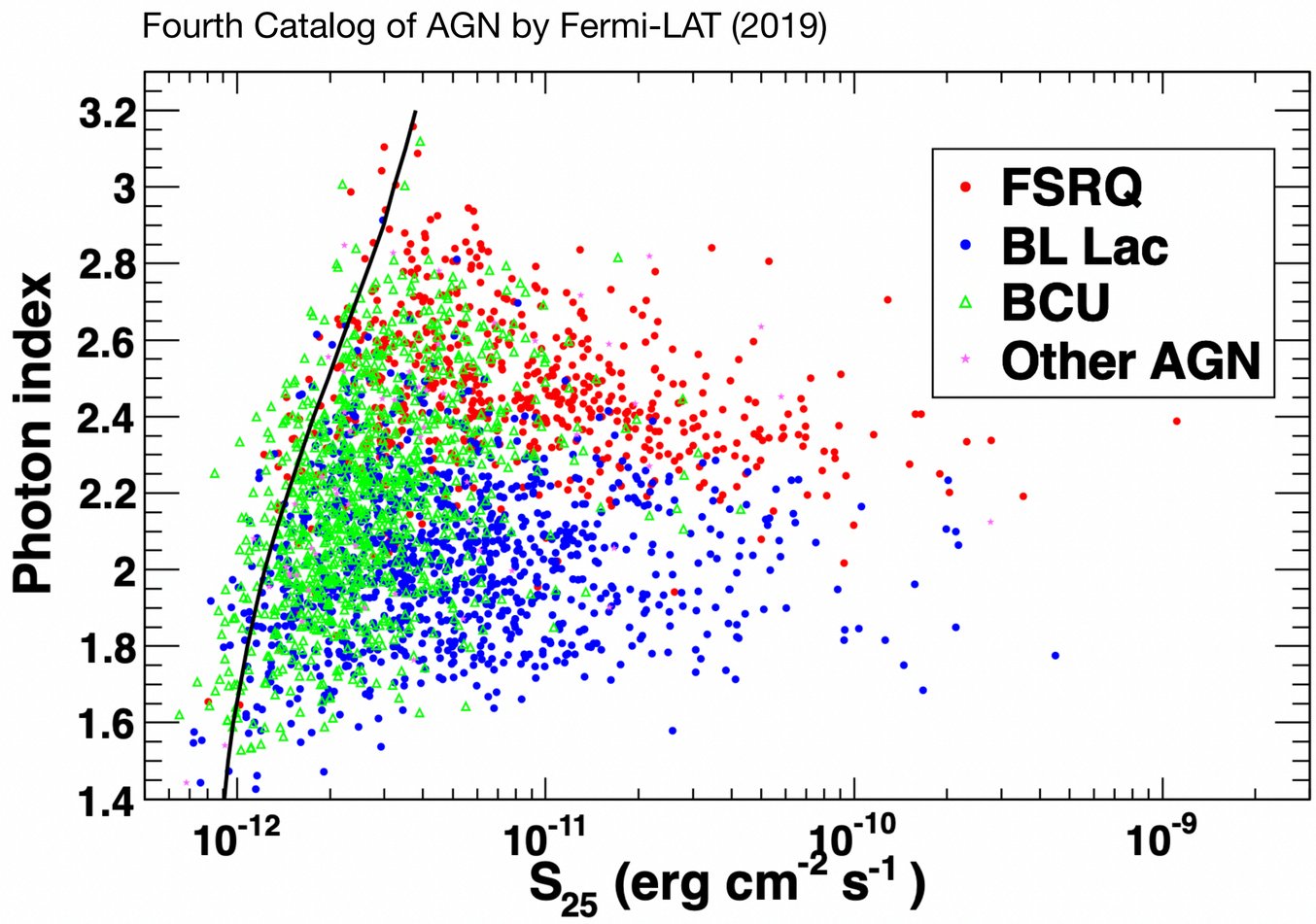

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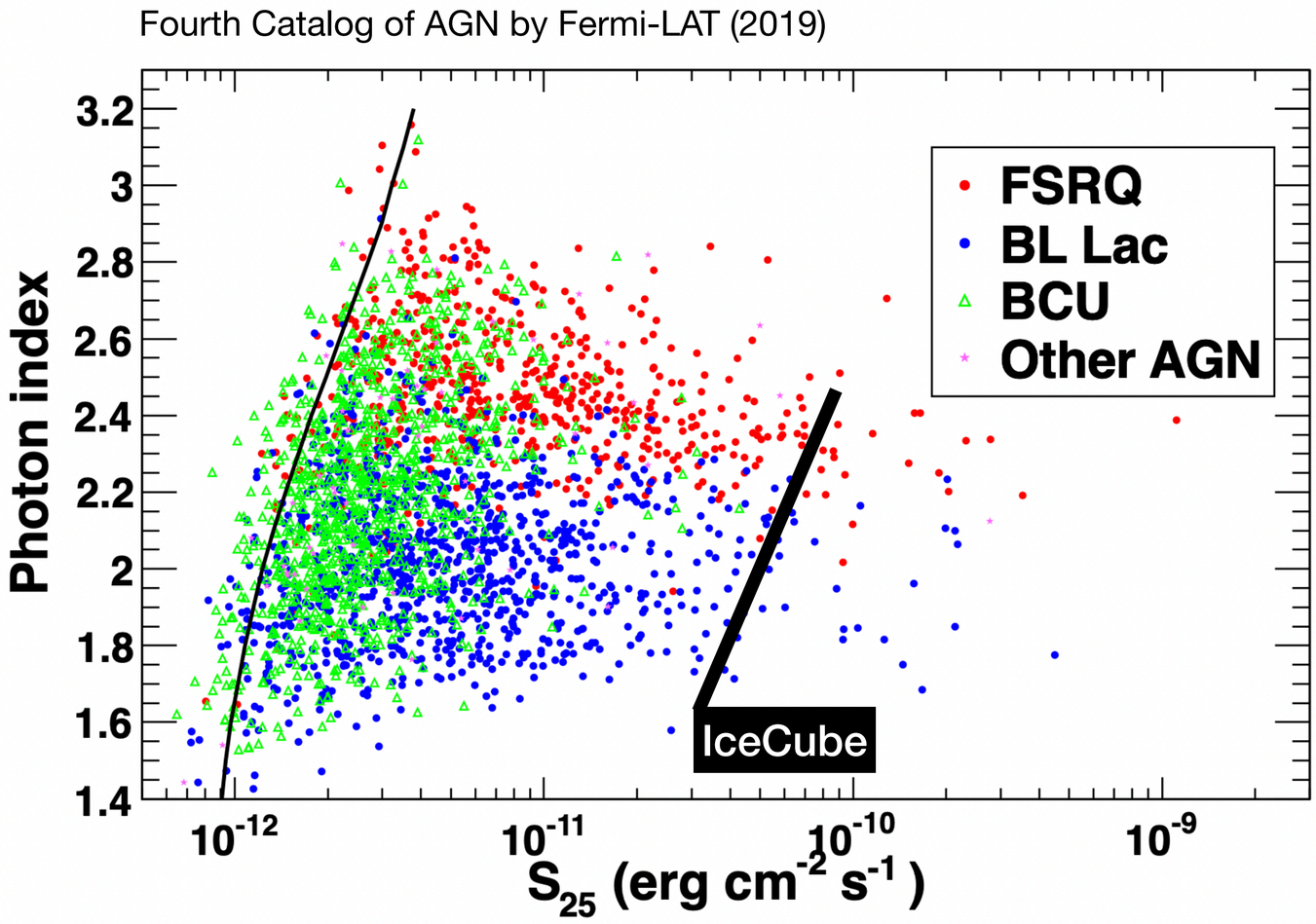

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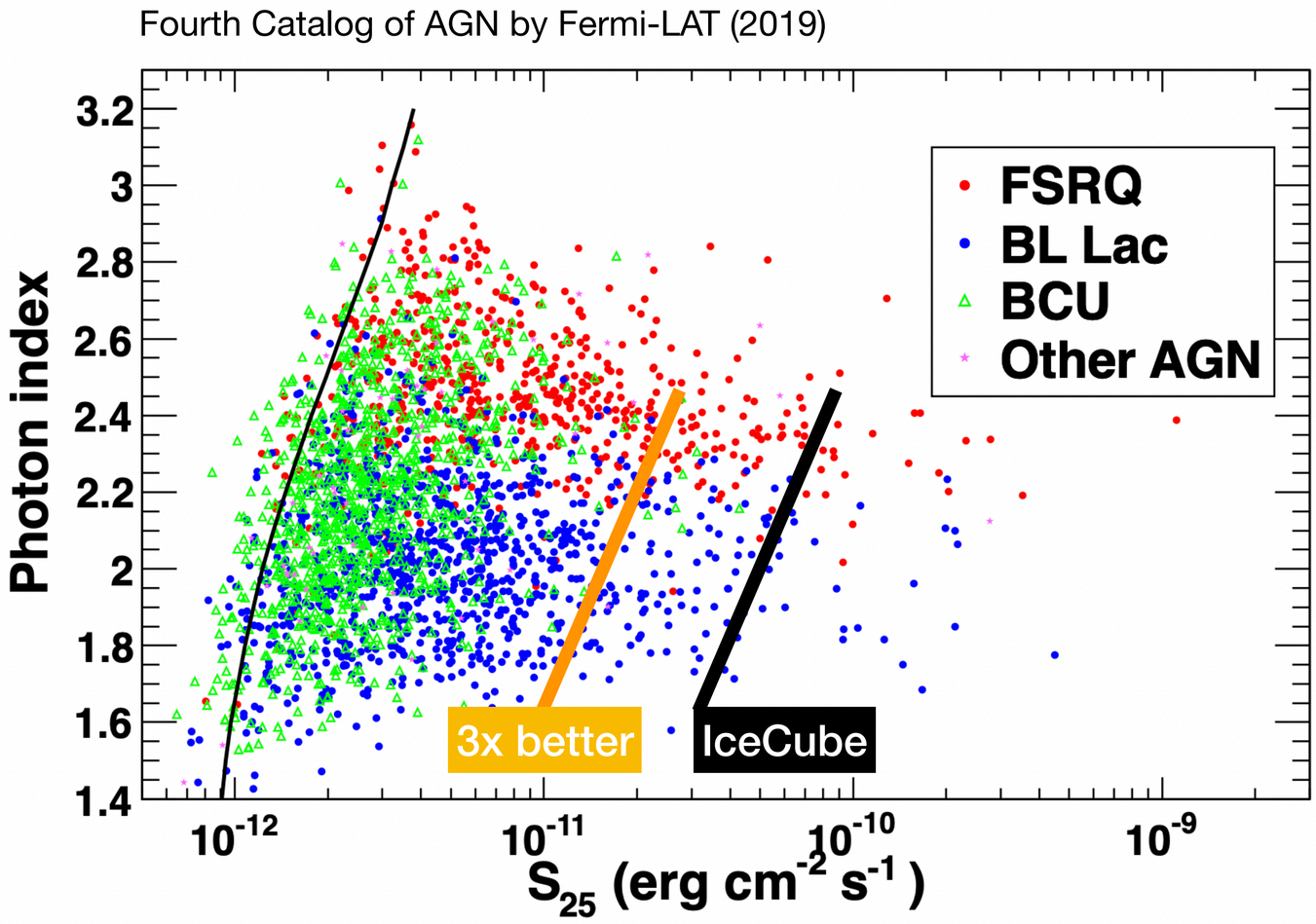
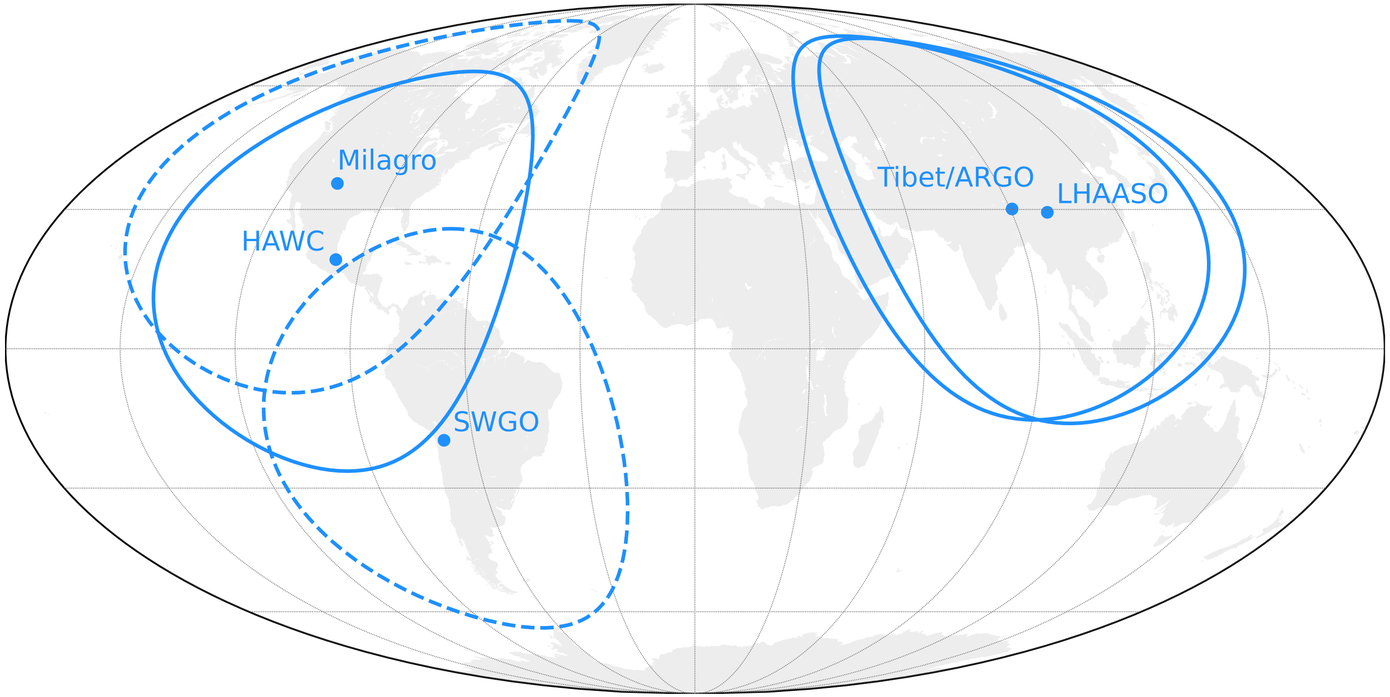


Moving Forward - We need more sky coverage

- **Southern sky has never been explored** by a wide-field air shower gamma-ray observatory
- More **instantaneous sky coverage** is needed to capture transients (GRB 221009A as a good example)



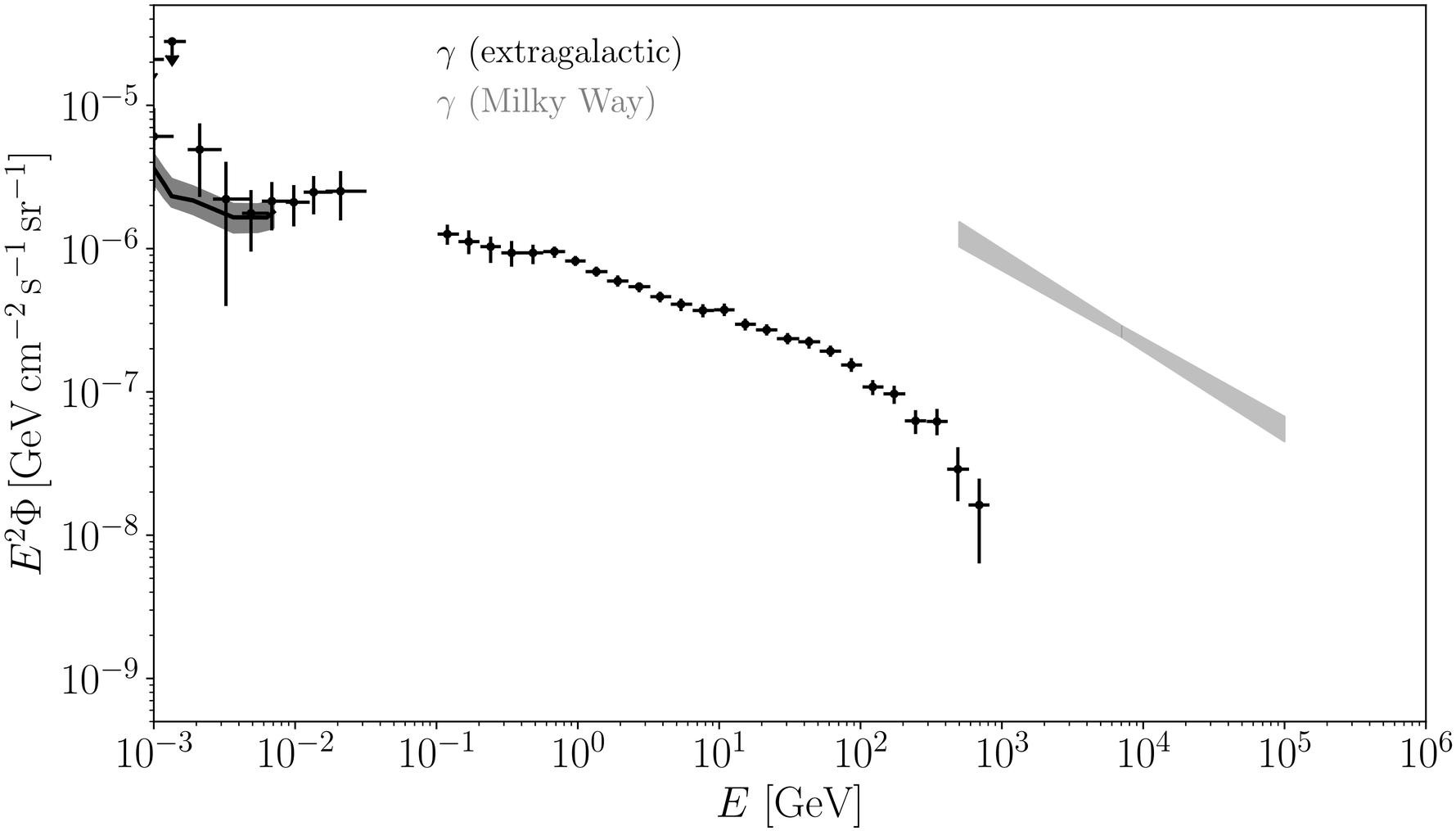
Plot credit: Marcos Santander

Gamma-ray Experiments

Large (>$200M)
Medium ($50-200M)
Small (<$50M)
Current/Funded
Space-based
International

Snowmass 21 CF1 report
Snowmass 21 CF7 report
Snowmass 21 white paper:
2203.07360

Gamma-ray Experiments



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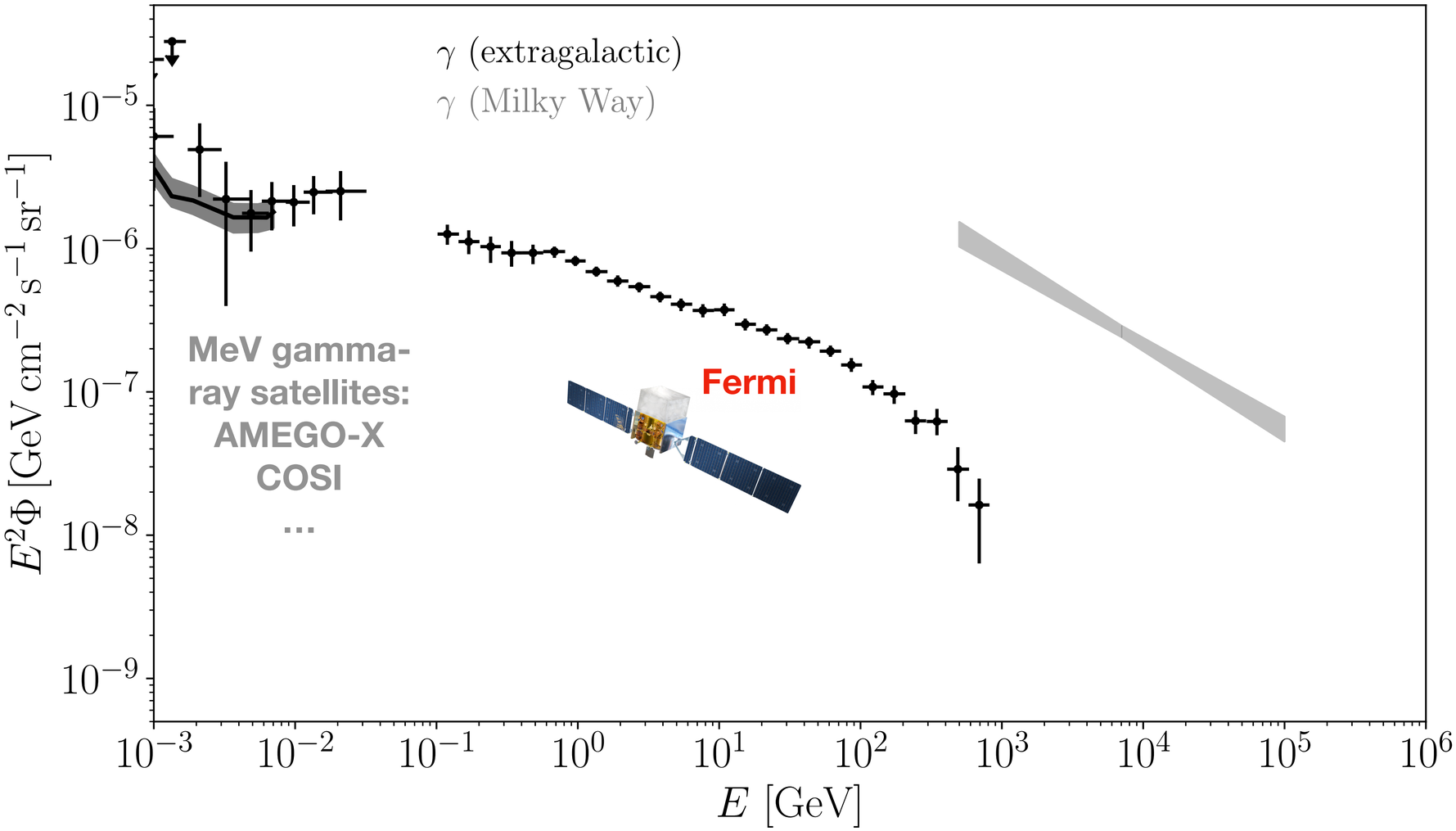

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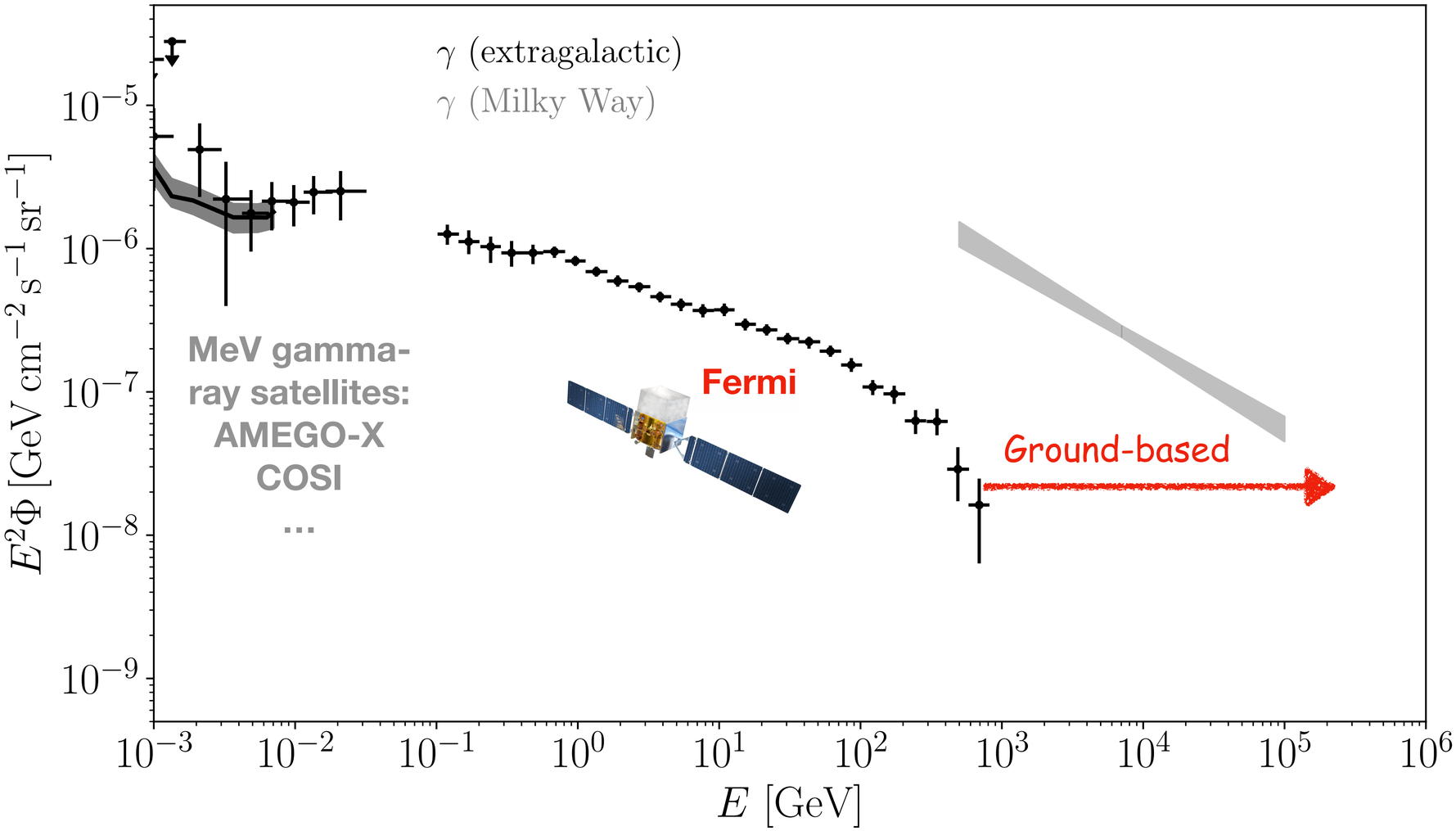
Snowmass 21 CF7 report
Snowmass 21 white paper:
2203.07360

Gamma-ray Experiments



Large (>$200M)
Medium ($50-200M)
Small (<$50M)
Current/Funded
Space-based
International

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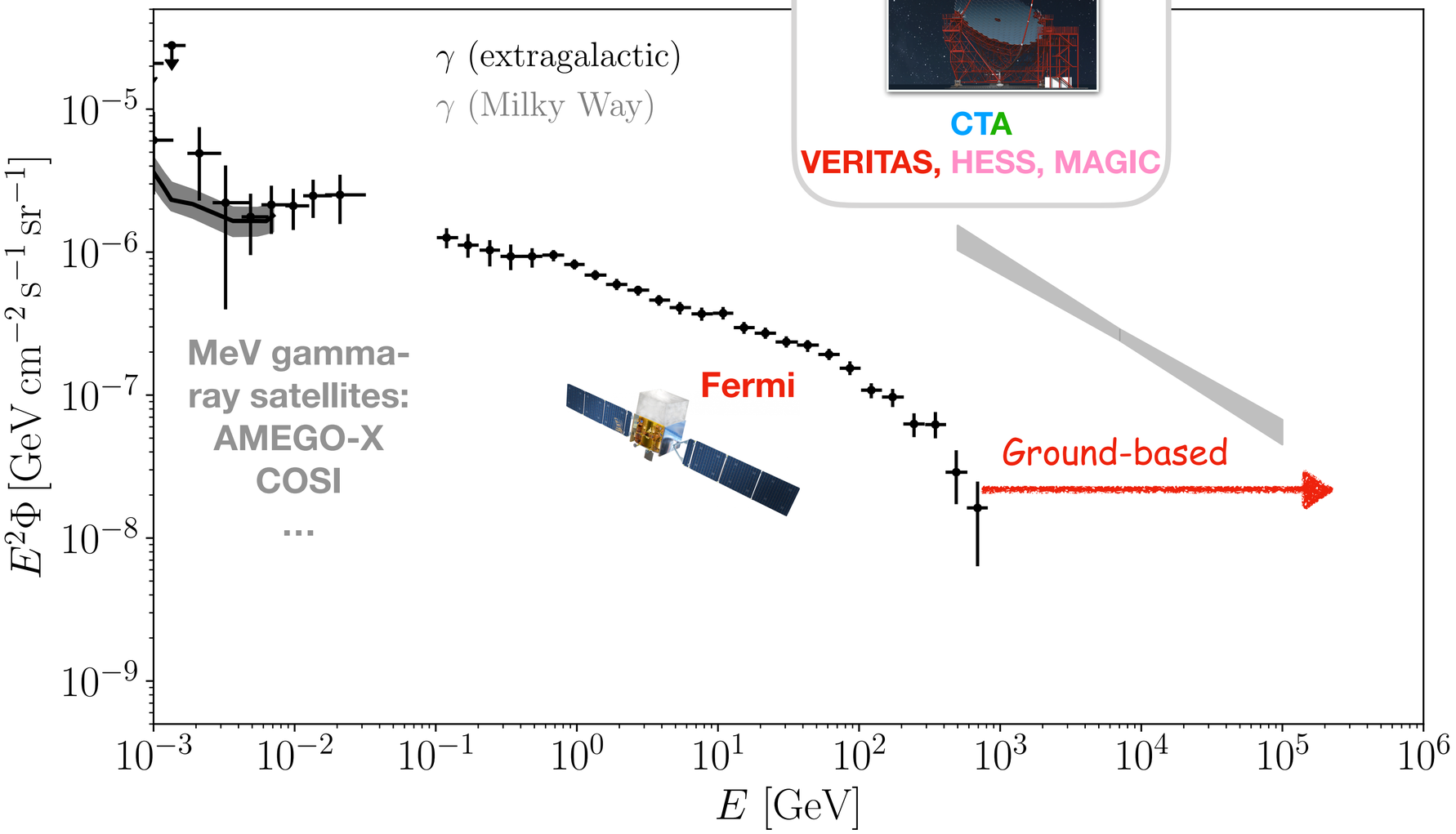

Imaging Atm. Cherenkov Telescopes (IACTs)

CTA
VERITAS, HESS, MAGIC

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Gamma-ray Experiments

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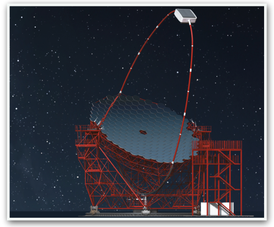
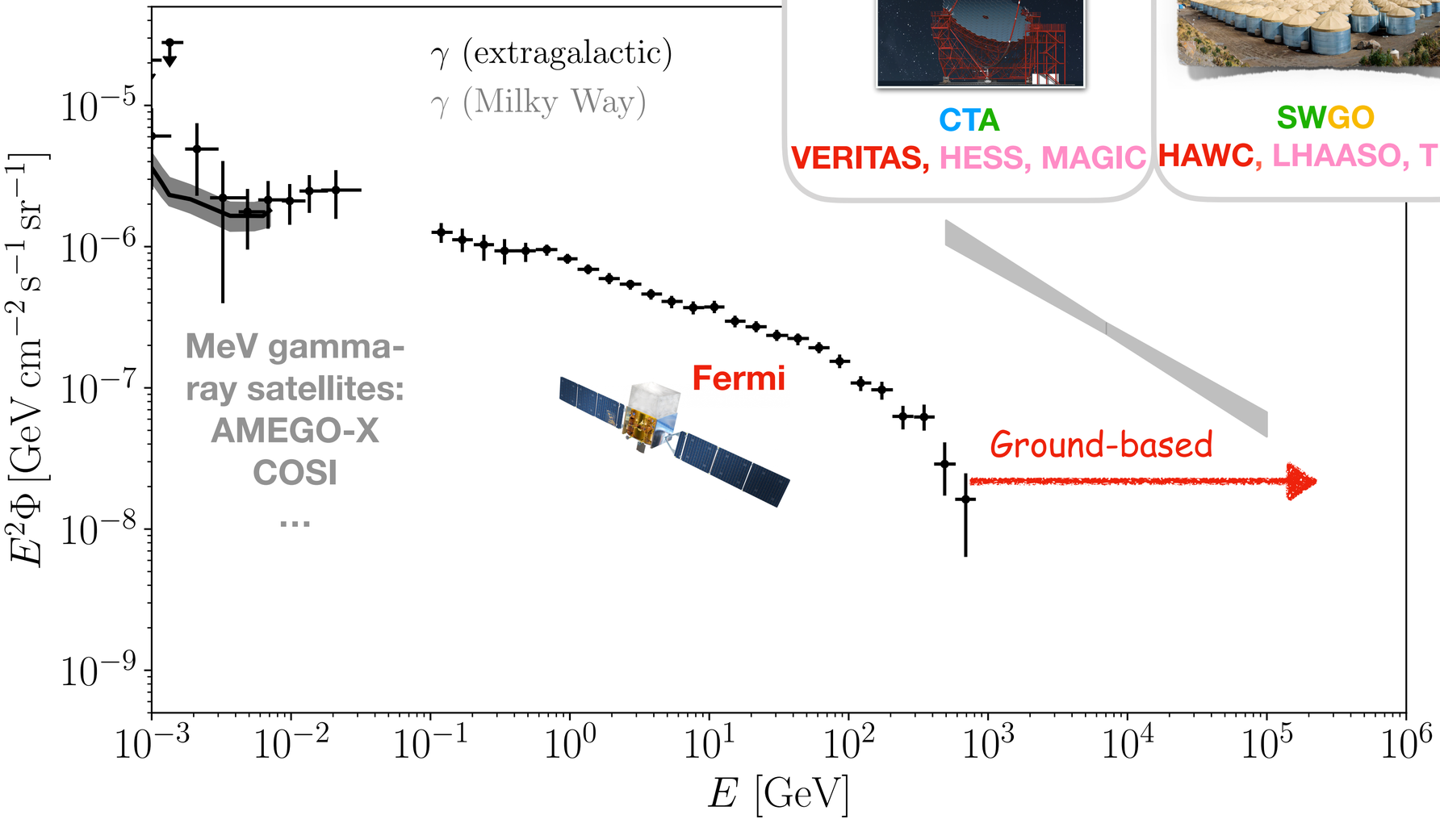


CTA
VERITAS, HESS, MAGIC

Air shower detectors

SWGO
HAWC, LHAASO, Tibet



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High and Ultrahigh Energy Neutrino Experiments

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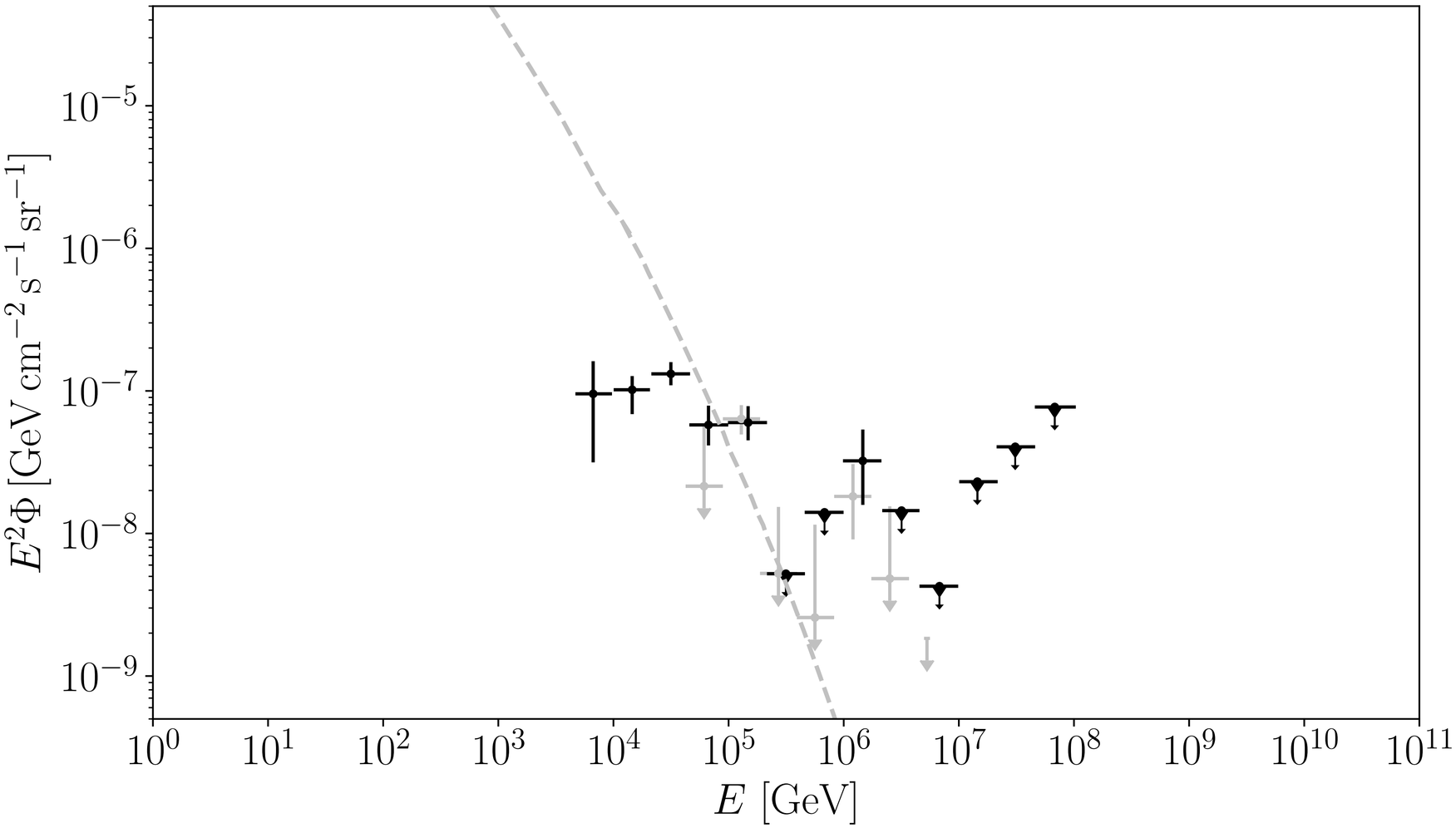
Snowmass 21 CF7 report
Snowmass 21 white paper:
2203.08096

See remarks by **Cosmin Deaconu, Kaeli Hughes, Matthew Potts, Tonia Venters, Nathan Whitehorn**

High and Ultrahigh Energy Neutrino Experiments



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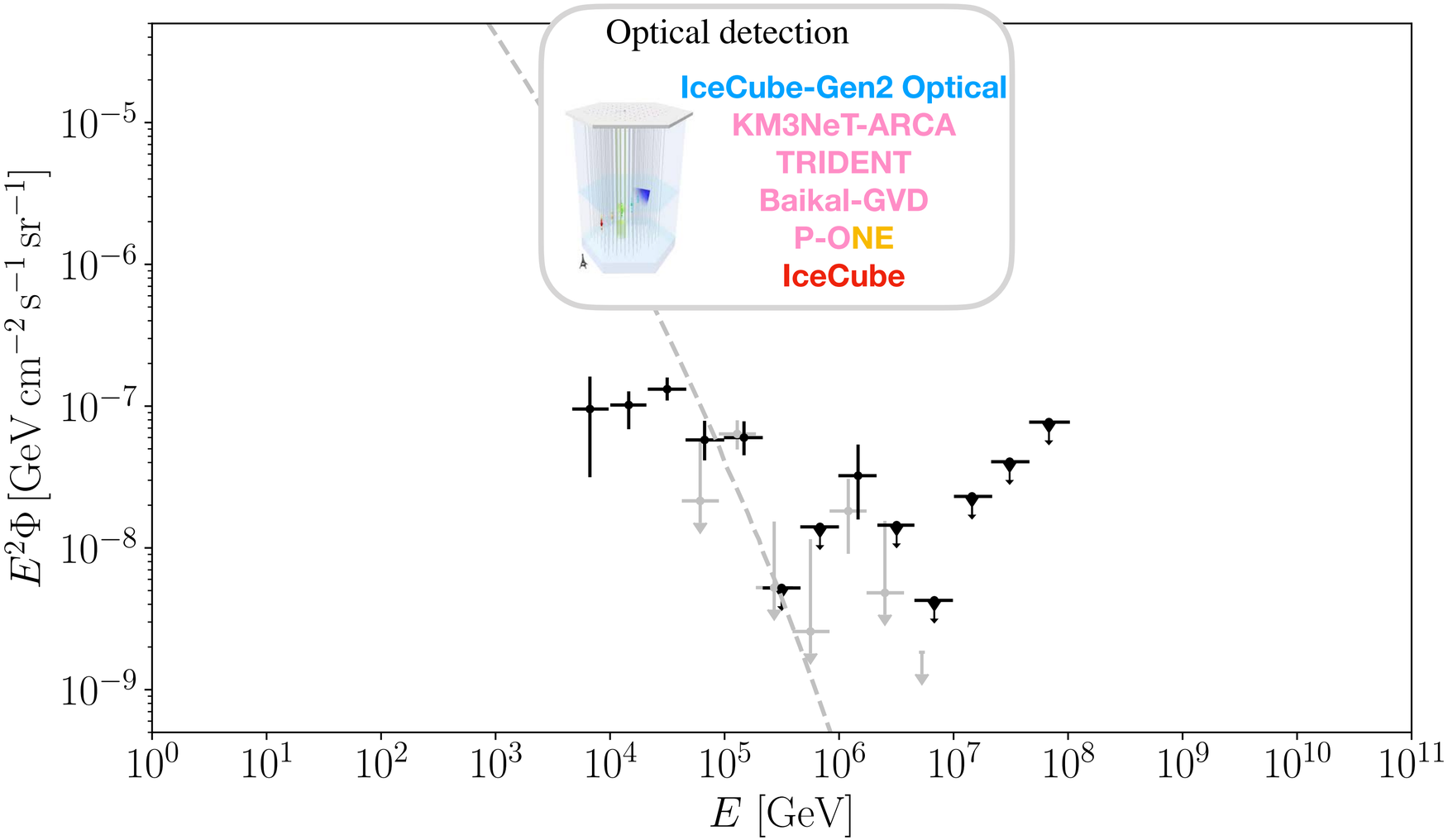

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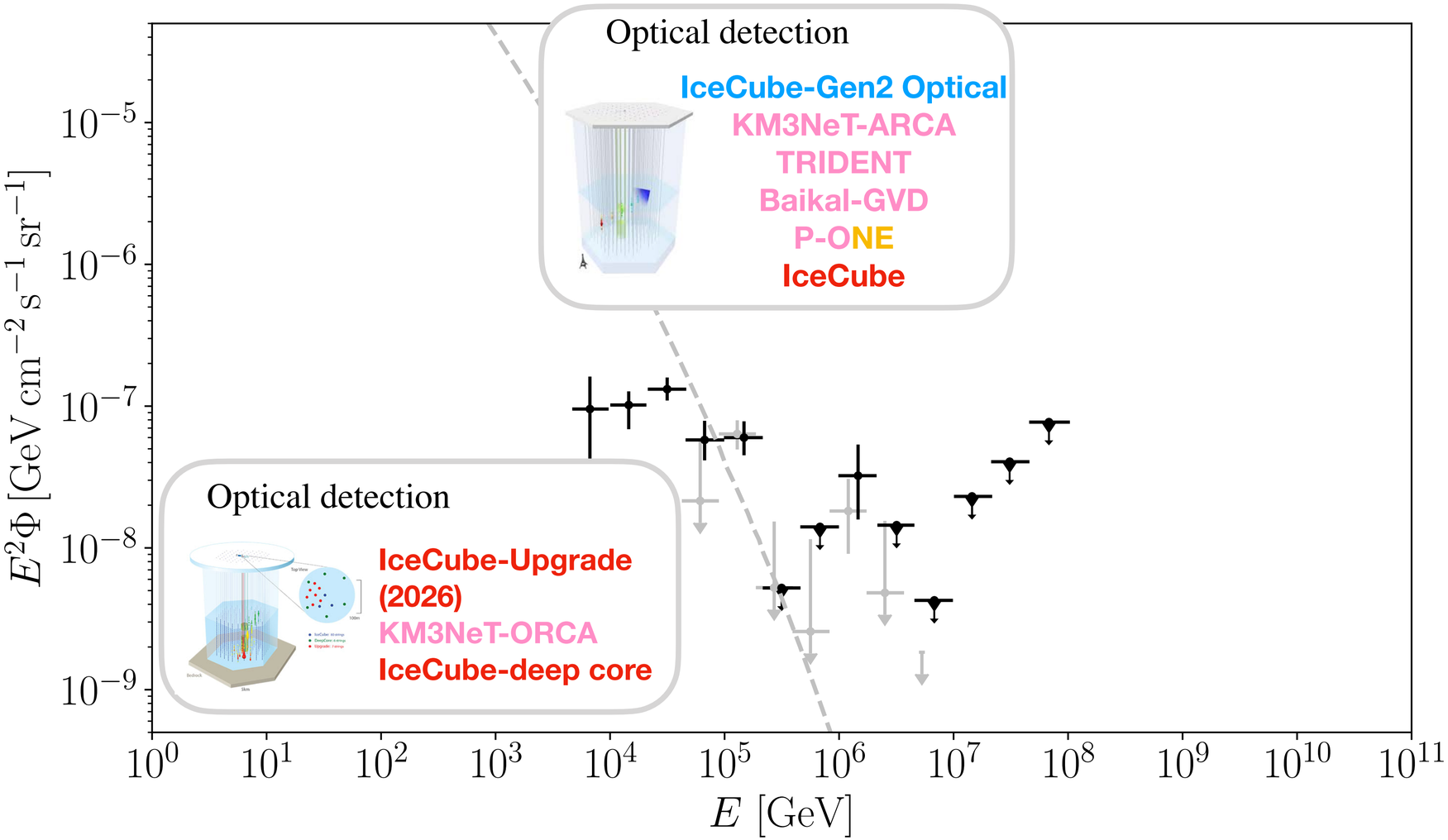
High and Ultrahigh Energy Neutrino Experiments



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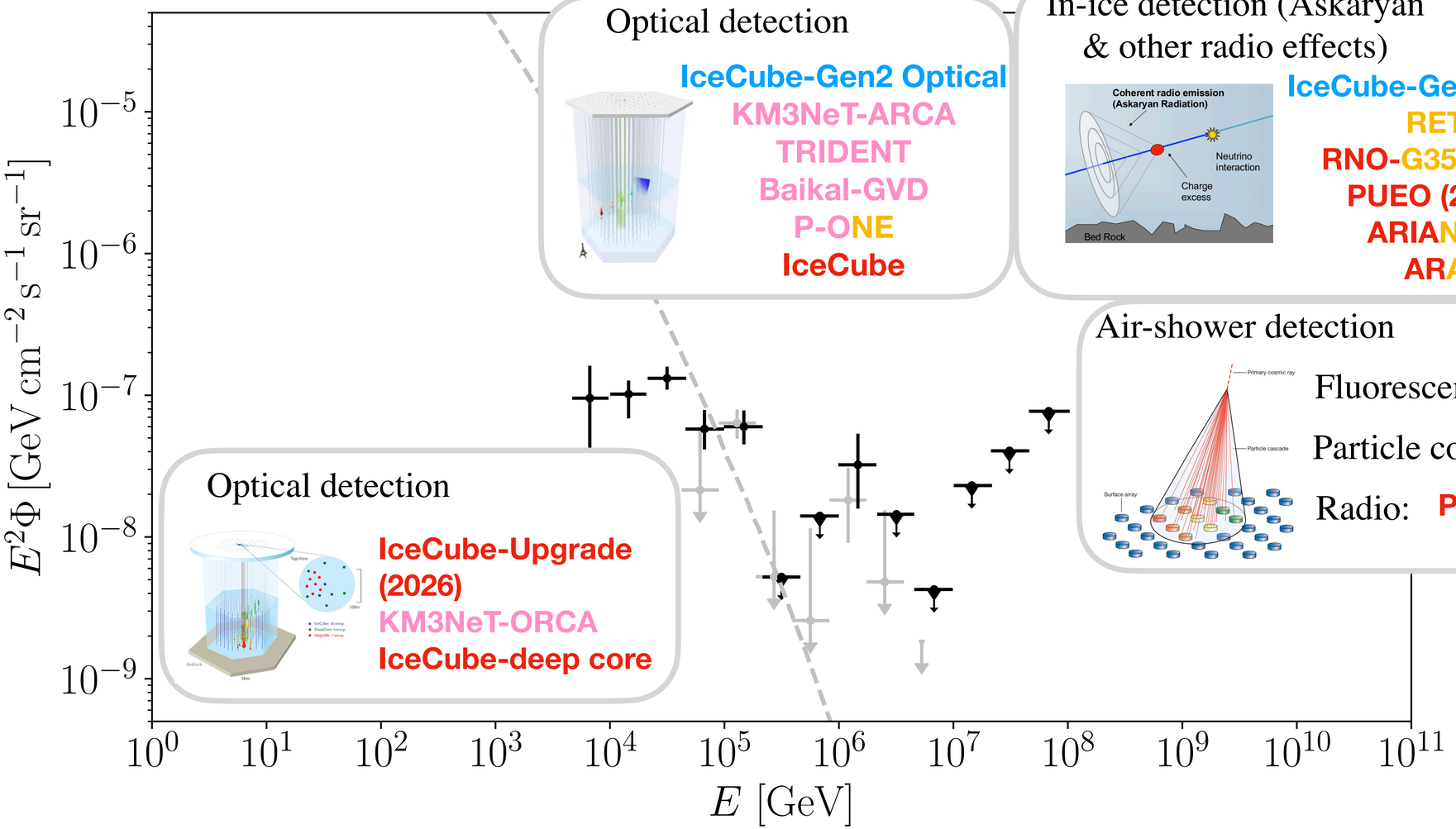

Optical detection

IceCube-Gen2 Optical
KM3NeT-ARCA
TRIDENT
Baikal-GVD
P-ONE
IceCube

In-ice detection (Askaryan & other radio effects)

IceCube-Gen2 Radio
RET
RNO-G35 (2026)
PUEO (2024)
ARIANNA
ARA

Air-shower detection

Fluorescence: EUSO-SPB2 (2023), Trinity, POEMMA, Ashra NTA, GCOS

Particle counters: TAMBO, GCOS

Radio: PUEO (2024), BEACON, TAROGE, GRAND, GCOS

Optical detection

IceCube-Upgrade (2026)
KM3NeT-ORCA
IceCube-deep core

Large (>$200M)
Medium ($50-200M)
Small (<$50M)
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Space-based
International

Snowmass 21 CF7 report
Snowmass 21 white paper: 2203.08096

See remarks by **Cosmin Deaconu, Kaeli Hughes, Matthew Potts, Tonia Venters, Nathan Whitehorn**

Ultrahigh Energy Cosmic-ray Experiments

Large (>$200M)
Medium ($50-200M)
Small (<$50M)
Current/Funded
Space-based
International

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300 → GRAND 10k → GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program → POEMMA
GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site → GCOS further sites

2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

Snowmass 21 CF7 report

See remarks by **Eric Mayotte** and **Frank Schroeder**

Conclusions

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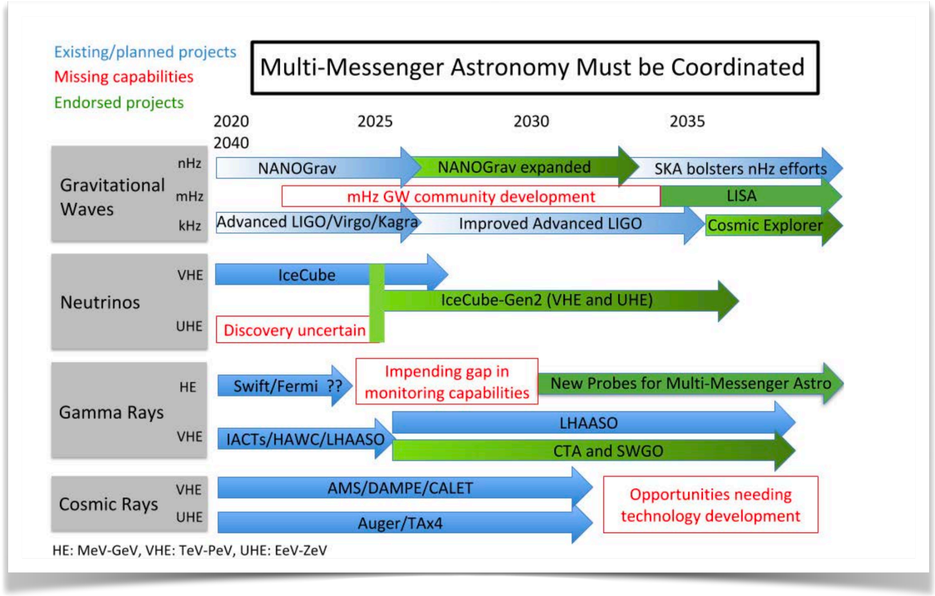
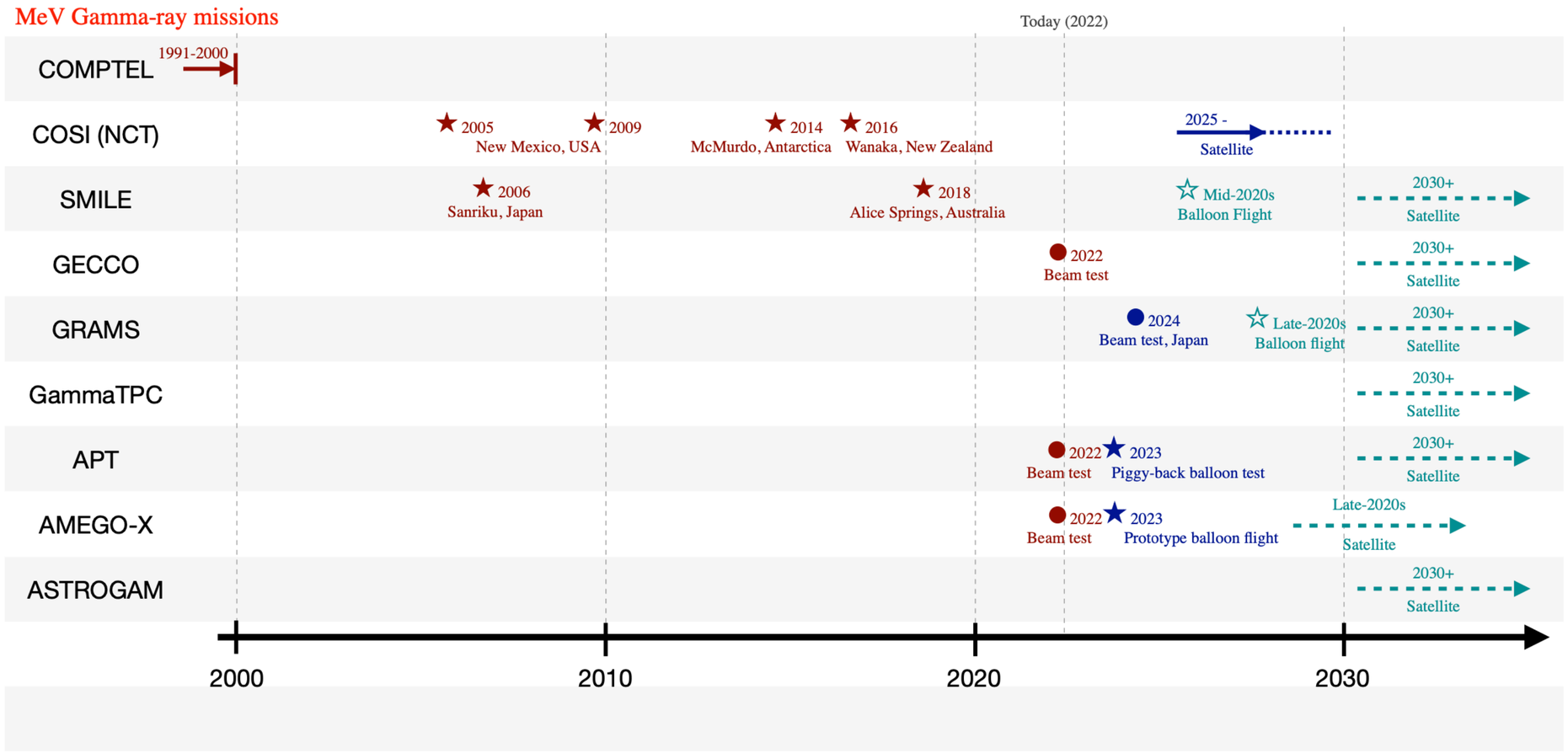
- “Cosmic-particle physics” is **complementary**
- Particles add to electromagnetic and gravitational waves to reveal the **unknown Universe** like never before
- Key to successes of the next decade: **better sensitivities** and **more sky coverage**
- Current-generation cosmic particle detectors are retiring. **New detectors are urgently needed**

Astro2020 Report by Panel of Particle Astrophysics and Gravitation



Backup Slides

MeV Gamma-ray Experiments



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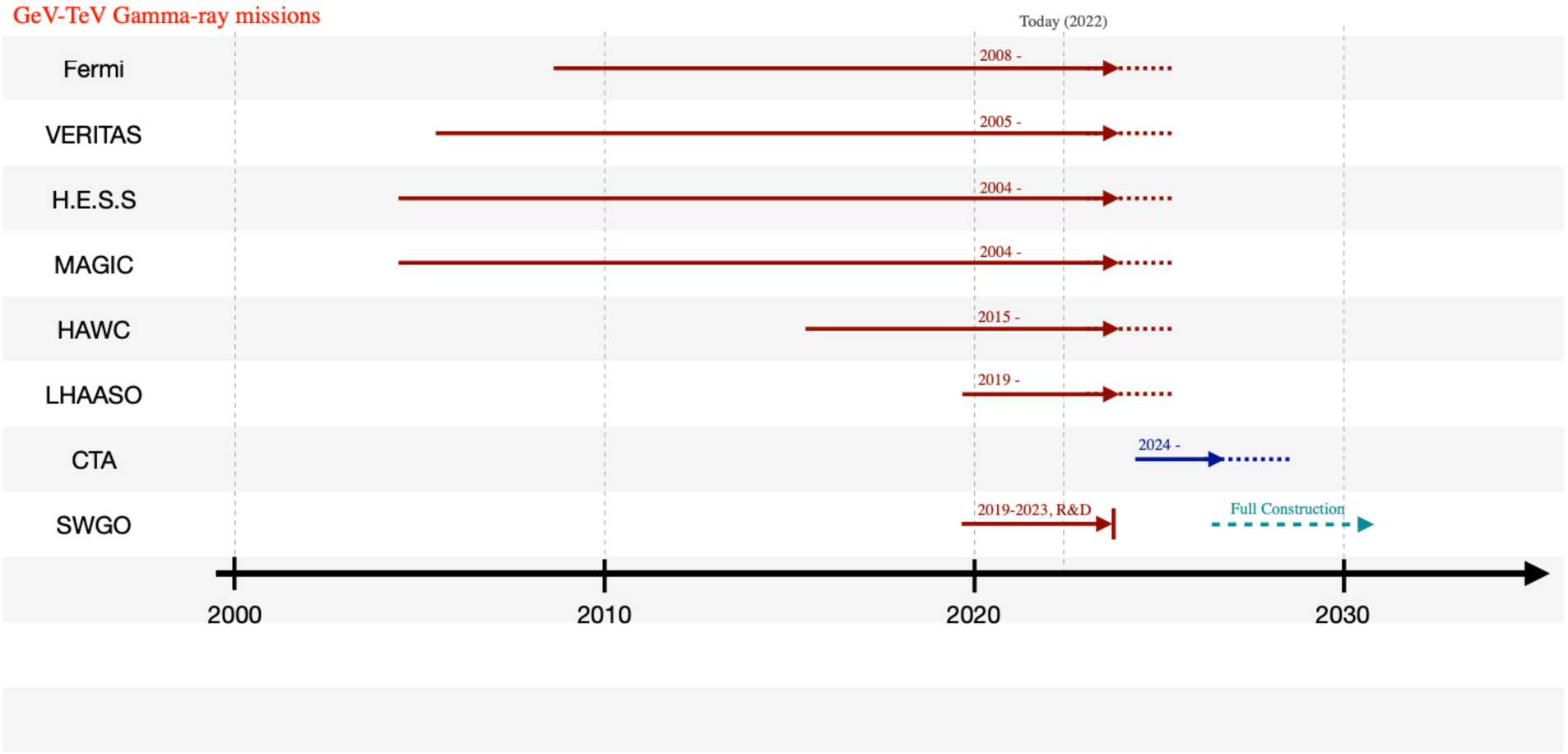
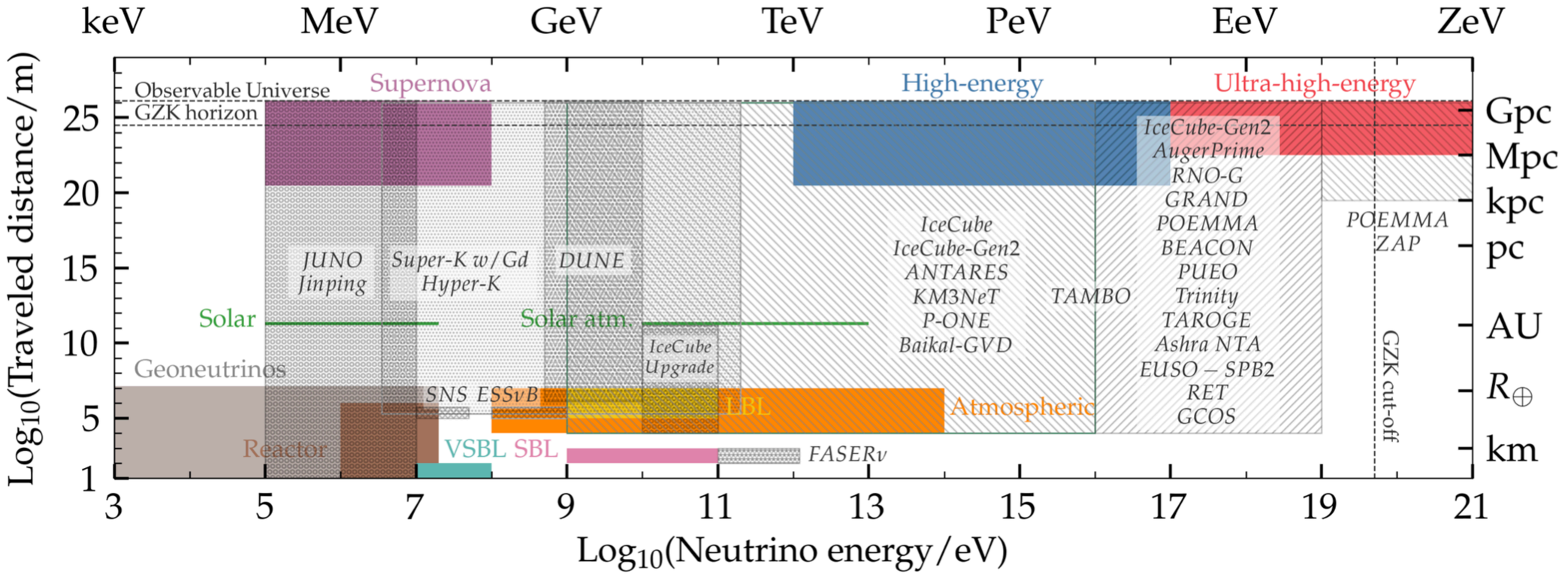
GeV-TeV Gamma-ray Experiments



Snowmass 21 CF1 report

Neutrinos Experiments



Funded, upcoming
US-lead

Snowmass 21 CF7 report

Effective area and angular resolution

Rough estimates

Fixed energy at 100 TeV

100 TeV (numu CC)	Instr. Volume (NC,nu-e, nu-tau)	Effective area nu-mu [m^2]	Ang. resolution [deg]
IceCube	1	100*	0.3
Baikal GVD	~0.4		0.1
KM3NeT ARCA	~1	100**	0.1
P-ONE	1 (cluster vol.,envelope: 3)		0.1
TRIDENT	7.5	~700**	0.1
IceCube Gen2	8	~300**	0.2

Refs.

https://doi.org/10.1016/j.jheap.2022.08.001

https://arxiv.org/pdf/2005.09493.pdf

trident: 2207.04519

IceCube: https://arxiv.org/abs/2008.04323. (and Tech. design rep in prep.)

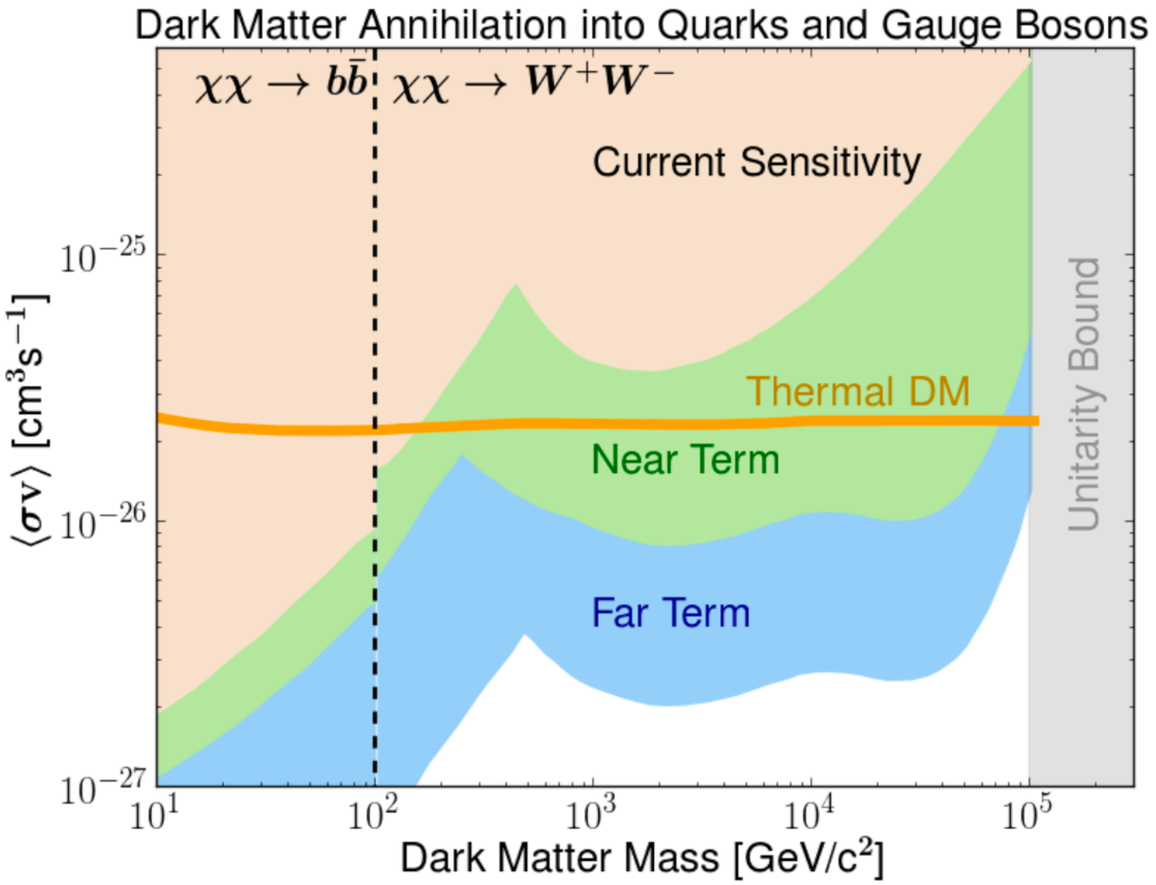
Baikal: Dzilkibaev, priv. comm.

+1 KM3 instr,
~3 km3 with empty space betw. clusters

*analysis level
** reconstruction level
***100m track length inside (~trigger level)

30

Slide from Albrecht Karle's talk at NCfA Symposium, 2023



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